Model development for a decision support system to promote an optimal use of pesticides in cotton production

Von der
Fakultät Architektur, Bauingenieurwesen und Umweltwissenschaften
der Technischen Universität Carolo-Wilhelmina
zu Braunschweig

Dissertation

von
Merimee, YANKE NANA
geboren am 04.12.1980
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List of symbols

Latin symbols		**dimension**
a	empirical parameter	[1]
A	adult stage population density (female adults)	$[L^{-2}]$
A_{rr}	adult resistant biotype density	$[L^{-2}]$
A_{rs}	adult heterozygous biotype density	$[L^{-2}]$
A_{ss}	adult sensitive biotype density	$[L^{-2}]$
B	biomass density of bolls	$[ML^{-2}]$
b	empirical parameter	[1]
B	density of the biomass	$[ML^{-2}]$
c	liquid phase concentration	$[ML^{-3}]$
$C(\psi)$	water capacity	$[L^3L^{-3}((MLT^{-2})L^{-2})]$
C_B	price of cotton	currency
C_e	environmental cost	currency
C_l	cost of pesticide application	currency
C_P	cost of pesticide	currency
D_A	dispersion coefficient	$[L^2T^{-1}]$
D_g	diffusion coefficient in the gaseous phase	$[L^2T^{-1}]$
D_h	coefficient of hydrodynamic dispersion	$[L^2T^{-1}]$
DT_{50}	time required for the chemical concentration under defined conditions to decline to 50% of the amount at application	[T]
E_{rr}	egg resistant biotype density	$[L^{-2}]$
E_{rs}	egg heterozygous biotype density	$[L^{-2}]$
E_{ss}	egg sensitive biotype density	$[L^{-2}]$
f_{oc}	fraction of organic carbon in the soil	[1]
g	gaseous phase concentration	$[ML^{-3}]$
H	density of the pest	$[L^{-2}]$
H_{rr}	larvae resistant biotype density	$[L^{-2}]$

H_{rs}	larvae heterozygous biotype density	$[L^{-2}]$
H_{ss}	larvae sensitive biotype density	$[L^{-2}]$
$\vec{J}$	flux density	$[ML^{-2}T^{-1}]$
$K(\theta) = K_r K_s$	hydraulic conductivity	$[LT^{-1}]$
K_0	capacity constant for biomass	$[ML^{-2}]$
K_{ap}	environmental capacity of larval life stage	$[L^{-2}]$
K_b	field carrying capacity for the boll biomass	$[ML^{-2}]$
K_B	half-saturation constant	$[ML^{-2}]$
K_d	sorption coefficient	$[L^3M^{-1}]$
K_d	sorption coefficient	$[L^3M^{-1}]$
k_l	liquid phase degradation coefficient	$[T^{-1}]$
k_{oc}	organic carbon sorption constant	[1]
K_r	normalized hydraulic conductivity	[1]
K_s	field carrying capacity for the stem biomass	$[ML^{-2}]$
K_s	saturated hydraulic conductivity	$[LT^{-1}]$
k_s	solid phase degradation coefficient	$[T^{-1}]$
L	biomass density of leaves	$[ML^{-2}]$
m	fitting parameter	[1]
n	fitting parameter	[1]
$\vec{q}$	volumetric water flux density	$[LT^{-1}]$
Q	source and sink term	$[ML^{-3}T^{-1}]$
r	proportion of females	[1]
r_b	growth rate for boll	$[T^{-1}]$
r_{max}	maximal growth rate for leaves	$[T^{-1}]$
r_s	growth rate for stem	$[T^{-1}]$
S	biomass density of stem	$[ML^{-2}]$
s	solid phase concentration	$[ML^{-3}]$
S_p	source term for pest population	$[L^{-2}]$
$S_w= S_w(\psi,x,y,z,t)$	source and sink term	$[L^3L^{-3}T^{-1}]$

t	time	[T]
t_{hr}	scale parameter of the dose response function	[1]
t_s	switching time	[T]
x	spatial coordinate	[L]
y	spatial coordinate	[L]
y_j	biomass density of organ j	$[ML^{-2}]$
z	spatial coordinate vertical direction	[L]

Greek symbols		**dimension**
μ	decay rate for leaves	$[T^{-1}]$
μ_A	natural mortality rate in the adult life stage	$[T^{-1}]$
μ_H	natural mortality rate in the larval life stage	$[T^{-1}]$
μ_j	attrition rate of organ j (may be time dependent)	$[T^{-1}]$
α	empirical parameter	$[L^{-1}]$
α_B	coefficient for the capacity function	[1]
$\alpha i,j$	interspecific competition coefficient between species i and species j	[1]
α_L	longitudinal dispersivity	[L]
α_s	velocity constant for sorption and desorption	$[T^{-1}]$
α_T	transversal dispersivity	[L]
β	maximal consumption rate	$[T^{-1}]$
γ	efficiency factor	[1]
γ_H	emergence rate	$[T^{-1}]$
ε	volumetric air content	$[L^3L^{-3}]$
η	form parameter of the dose response function	[1]
θ	volumetric water content	$[L^3L^{-3}]$
θ_r	residual water content	$[L^3L^{-3}]$
θ_s	saturated water content	$[L^3L^{-3}]$
ρ	bulk density	$[ML^{-3}]$
σ	empirical parameter	[1]
σ_x	standard deviation in the x direction	[L]
σ_y	standard deviation in the y direction	[L]
φ_H	oviposition rate	$[T^{-1}]$
ψ	soil matric potential	$[(MLT^{-2})\ L^{-2}]$

Acronyms

a.i.	:	active ingredient
CIRAD	:	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
EPPO	:	European and Mediterranean Plant Protection Organization
GAP	:	Good Agricultural Practices
GDP	:	Gross Domestic Product
H.A.	:	*Helicoverpa armigera*
IPM	:	Integrated Pest Management
ODE	:	Ordinary Differential Equation
PDE	:	Partial differential equation
SQP	:	sequential quadratic programming
Sodécoton	:	Société de Développement du coton
SUCROS	:	Simple and Universal CROp growth Simulator
UNPCB	:	Union National des Producteurs de Coton du Burkina

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Zusammenfassung

In dieser Arbeit beschreibe ich die Entwicklung eines Entscheidungsunterstützungs-Systems mit dem Ziel der optimierten Verwendung von Pestiziden in der Landwirtschaft, um das Risiko für das Auftreten von Resistenzen bei den Zielorganismen und die Verschmutzung von Wasserressourcen zu minimieren. Die dafür verwendeten Methoden sind eine Sammlung mathematischer Teilmodelle für die Simulation der Dynamik von Kulturpflanzen und Schädlingen und des Umweltverhaltens von Pestiziden. Dabei wurden unterschiedliche mathematische Ansätze verwendet: zeitkontinuierliche Modelle in Form eines Systems von gewöhnlichen Differentialgleichungen für das Wachstum von Baumwollkulturen und für die Kinetik von Insektiziden und in Form von partiellen Differentialgleichungen für die räumliche Ausbreitung von Schädlingen und Pestiziden in Böden sowie ein zeitdiskretes Modell für die Populationsdynamik von alters- und stadienstrukturierten Populationen.

Die Teilmodelle wurden separat getestet, um sie zu verifizieren. Für das Teilmodell für die Bestandesdynamik von Baumwolle konnte anhand von Literaturdaten eine Parameteridentifikation durchgeführt werden. Das Entscheidungsunterstützungs-System ergab sich dann aus der Integration der Teilmodelle. Die Modelle wurden in die numerischen Programmierumgebung Matlab implementiert. Für die Lösung der partiellen Differentialgleichungen wurde das Finite-Elemente-Tool COMSOL Multiphysics verwendet.
Verschiedene Tests wurden durchgeführt, um das Modellverhalten auf Plausibilität zu überprüfen: Syntaxprüfung, Stresstests mit extremen

Parameterwerten und Vergleich mit Messdaten. Das Verhalten des Modells in Bezug auf die Parameter-Variationen folgte den erwarteten Trends. Anhand einer geeigneten Zielfunktion, die ökonomische Kriterien mit fiktiven Umweltkosten verknüpft, wurden Kontrollmaßnahmen bewertet.

Die Anwendung des integrierten Modells auf die Entwicklung optimaler Managementverfahren zur Bekämpfung des Baumwollschädlings *Helocoverpa armigera* im Anbaugebiet von Burkina Faso führte zu erheblichen Modifikationen der praxisüblichen Verfahren.

Jedoch sind mehr Tests und Anwendungen in verschiedenen Anbaugebieten notwendig, um die hier vorgestellte Methode effektiv auf andere Kulturen und Schädlinge zu übertragen.

Summary

In this thesis, we proposed and described well organized materials for the development of a Decision Support System aiming at the optimal allocation of pesticides in agriculture, given that resistance can develop in the target population, and pesticides environmental pollution, mainly water resources, can occur. These materials are a collection of mathematical sub-models, simulating the dynamics of crops and pests and the environmental fate of pesticides. Different mathematical approaches were used: continuous time models in the form of ordinary differential equations for the growth of cotton crop and for the kinetics of insecticides; in the form of partial differential equations for the spatial spread of pests and pesticides in soil and a discrete time model for population dynamics of age and stage structured populations.

For the cotton crop dynamics sub-model, parameter estimation was carried out based on literature data. The Decision Support System was then constructed by integrating the sub-models. The models were implemented in the numerical programming environment Matlab. For the solutions of the partial differential equations, the finite elements tool COMSOL Multiphysics was used. Various tests were carried out to verify the model behavior for plausibility: syntax check, stress tests with extreme parameters values and comparison with measured data. The behavior of the model with respect to parameters variations followed expected trends. Using a suitable objective function, control

measures were evaluated including economic criteria with fictive environmental costs.

The application of the integrated model to the development of better management practices for the control of the cotton pest *Helocoverpa armigera* in the growing areas of Burkina Faso led to substantial modifications of the usual practical method.

However, more tests and applications are necessary in different production areas to effectively transfer the method presented here to other crops and pests.

1. Introduction

According to Statista (2014), the world population is estimated to be over 6.9 billion and is increasing. Therefore, agricultural production must be expanded or made more efficient to meet nutritional needs. Crop yields are increasing; however, the percentage of yield lost to pest is increasing as well in most cases (Brown 1996). Insect pests are a major constraint on production and their management imposes significant costs and environmental problems (Fitt 2000). There is therefore the need of intensive pest control. While many components of IPM have been implemented, the main intervention for the management of key pests continues to be insecticides (Fitt 2000). But the situation of pest control viewed over recent decades is one in which both pesticide use and pest damage is increasing. Yudelman et al. (1998) reported the paradox of increased pesticide use and increased losses from pests. For the pest *Helicoverpa armigera (H.A.)*, McGahan et al. (1991) reported that direct damage to flowering and fruiting structures by larvae, and extensive insecticide spraying result in low yields and high control costs. Moreover, Fitt (2000) argued that dependence on pesticides is unlikely to be sustainable and brings with it considerable economic costs (A$300-A$600/ha in Australia), ecological problems from pesticide resistance in key pests, and environmental concerns arising from residues in soil and water and drift of pesticides into non-crop environments. Even with the implementation of intense efforts to control insects, pest management persists as a significant challenge for this century (Ferron and Deguine 2005). The use of pesticides has been increasing in many parts of the world, and their excessive application is a really threat to the environment (Altieri 1999). The reduction of the use of chemical pesticides is a permanent goal in sustainable agriculture. Due to the enormous variety in different types of pesticides, crops, hydrological and soil conditions and the application time of pesticides, the use of computer simulation models is indispensable (Groen 1997). Calling for accurate predictions of pest outbreaks and optimal insecticides application schemes, we suggest a set of materials toward this direction, to develop a Decision Support System (DSS) with components overviewed in figure 1. The DSS is based on mathematical models whose criterion of optimization aims at maximizing the net gain in production. To achieve this, we will formulate a time continuous model for crop dynamics and a time continuous model for insecticide-stressed pest population dynamics in interactions, with ordinary differential equations (ODEs). Another approach will be a hybrid model to study interactions between crop and insecticide-stressed pest dynamics, computed as a sequence of initial value problem for the crop growth model. For the hybrid model, the pest population dynamics is a discrete-time model, the extended Leslie model, used in this thesis to simulate the temporal dynamics of *Helicoverpa Armigera* in a daily time step. Spatial spread of pest will be considered and implemented into the finite element tool COMSOL Multiphysics. Evolution of resistant pest via population genetics will be described with partial differential equations (PDEs). The gain sensitivity to parameters will be analyzed to identify which parameters need more attention when making decisions based on this DSS.

The simulation model developed in this study can help to simulate crop and pest population dynamics in interaction and evaluate the efficiency of insecticides-pest management strategies. Therefore improve field yield, quality of crop, profitability of the speculation and ecologically farming. The model will contribute to avoid everyday pest tracking and counting for the attainment of the economic threshold. With the combination of population dynamics and population genetics, the model will enable the examination of how new insecticidal technologies affect the area-wide pest populations, and how the pest populations can respond evolutionarily (Peck et al. 1999, Storer et al. 2003).

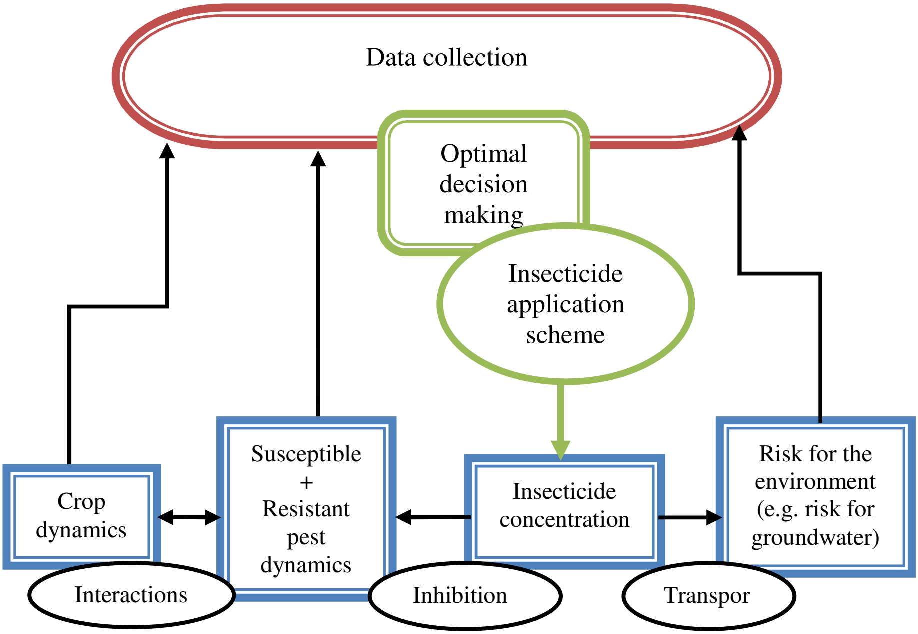

Figure 1: Conceptual components of the DSS and their interrelationships

1.1. *Scope of the study*

Within the scope of the EXCEED (EXCELLENCE CENTER FOR DEVELOPMENT COOPERATION SUSTAINABLE WATER MANAGEMENT) project, funded by the German Ministry for Economic Cooperation and Development, and the DAAD (German Academic Exchange Service), this study was undertaken to prevent water resources from pollution by pesticides in agriculture in Burkina Faso. Thus, most of considerations and examples are taken with an idea of application in Burkina Faso. Nevertheless, achievements of this work can be applied to specific cases under specific conditions for realistic decision making.

Figure 2: Location of Burkina Faso in Africa
Source: One World Nations Online

Burkina Faso is a Sahelian country of 274 000km^2 in West Africa (figure 2). The population is about 10.32 million with a density of about 37.6 habitants per square kilometer according to the 1996 demographic survey (Convention-cadre des Nations Unies sur les changements climatiques 2001). The country is bathed in a dry tropical climate of the type Sudanese. The pluviometry decreases form the South-West to the North. Temperature is made of great season variations and strong diurnal amplitudes mostly in the North of the country. The hydrographic network of Burkina Faso is however quite dense but more often without water.

Burkina Faso is facing crucial environmental issues primarily marked by the almost endemic phenomenon of draught and desertification. This situation is aggravated due to anthropogenic activities mainly agriculture. Farmers of Burkina Faso as most of West African farmers are vulnerable to climate variability (Berg et al. 2009, Simonsson 2005) and low soil fertility though agriculture plays an important role in the national economy. Agriculture employs almost 90% of the active population and represents over 30% to 38% of Gross Domestic Product (GDP) and practically half of exportations (Stads and Boro 2004, Vognan et al. 2002). Cotton alone represents 40% to 50% of exportations earnings and satisfies 40% of the national oil consumption. The cotton grain is also a food supply for human and some animals such as cattle. Cotton culture occupies a prominent place in the development of the national economy of Burkina Faso (Gomgnimbou et al. 2009). In Burkina Faso, cotton commercialization represents more than half export income. This cash crop is produced in the western provinces of the country where average annual precipitations are over 700mm allowing cultivation without irrigation (Hauchart 2008) and yields are less than 3000 kg/ha (Koulibaly et al. 2009).The cultivation of this important crop needs the use of too much pesticides more than any other crop (Savadogo et al. 2006), and cotton is likely to be an important host plant with respect to resistance because pesticide usage is heaviest in this crop compared with other crops and native vegetation (Daly 1993). These pesticides are capable of huge damages at three levels:

- Toxicity of pesticides to agricultural users and professionals of phytosanitary industry (Toe et al. 2000, Toe et al. 2002);
- Toxicity for the consumer, due to the presence of toxic residues (Fournier and Bonderef 1983);
- Pollution and environmental toxicology (Ramade 1992, Toe et al. 2004).

Environmental toxicology is our main focus regarding the transport of pollutants to water resources. Fresh water shortage is common in Burkina Faso as in most of West African countries and drinking water supply comes directly from groundwater or surface water in rural areas.

For a sustainable agriculture, the government of Burkina Faso gives a high priority to agriculture research and development. Efforts are also made to restore, enhance and protect the environment through surveys and practical actions on the dynamic of the environment (Compaore and Doamba 2005).

1.2. Aim of the study

The present research project focuses on the development of a decision support system (DSS) allowing decision aid in the implementation of good agricultural practices (GAP). The DSS is based on mathematical models. The objective of this modeling effort is to predict crop response to pesticide-stressed pest population dynamics and the potential contamination of the environment. The completion of this work will help to improve agricultural pests management minimizing environmental damage. The main benefits of such a DSS are ecological and economic. This project also aims to demonstrate that coupling an agricultural system with a GIS application at landscape level is feasible. This allows us to profit from knowledge of how the system functions in order to better understand and manage crop-pest-pesticides systems.

2. General information

2.1. Cotton plant

There are several species of cotton; some of them are: *Gossypium arboretum*, *Gossypium barbadense*, *Gossypium hebaceum* and *Gossypium hirsutum* which is consider in this study. Cotton plant is dicotyledonous and belongs to the family of Malvaceae, as okra, jute and cacao. It is a shrubby plant with less than 1 to 2 meters height, cultivated as an annual crop in Burkina Faso as in many other countries. Cotton culture is best suited under an annual pluviometry of 700 mm with 120 to 125 watered days (Sément 1986). The main organs of the plant are leaves, stem and bolls (figure 3 and 4). Its development cycle from sowing to harvest varies between 150 and 175 days according to the variety, the agroecological area and the sowing dates (Ochou et al. 2006). Cotton bolls range in size from under 3 grams to over 6 grams per boll. Seed accounts for about 60% of this weight (Oosterhuis 1994, Marani 1979);

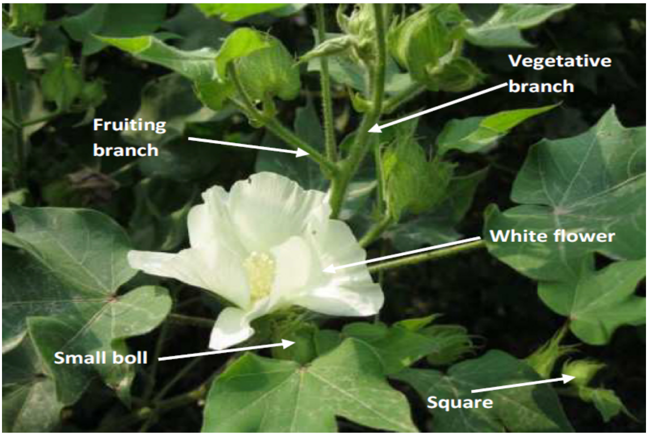

Figure 3: A cotton plant

Figure 4: Matured cotton boll

Cotton is non-determined growing plant that is able to compensate lost of fruiting organs (Nibouche et al. 2002) and each cotton season presents its own unique challenges based on current conditions and past experiences (Robertson et al. 2007). Boll shedding is common in cotton culture; this may be an important natural process by which the plant adjusts its fruit load to match the supply of inorganic and organic nutrients (Oosterhuis 1994). This suggests that a limited amount of shedding is normal and perhaps necessary for good quality and yields. Shedding is generally attributed to physiological or insect causes.

2.2. Helicoverpa Armigera

Helicoverpa armigera (Hübner) is one of the world's most destructive agricultural pests in general, and cotton (*Gossypium hirsutum)* insect pests in particular (Djihinto et al. 2009). It is a major pest of a wide range of plants, including field and horticultural crops in many parts of the world (Mironidis and Savopoulou-Soultani 2008, Sullivan et al. 2010, Kumar et al. 2009, Srinivasan 2010, Wu et al. 2004). The larvae of this bollworm also attack tomato, corn, tobacco, chick pea, pepper, okra, sorghum, sunflower, carnation, and gladiolus. The annual control costs and production losses worldwide amount to $5 billion (Lammers et MacLeod 2007) and approximately $225.2 million in Australia (Clearly et al. 2006).

The caterpillars attack and destroy the buds, flowers and bolls. Larvae are too voracious. Traore (2008) reported that one larva may destroy 5 to 10 reproductive organs per day, in particular squares (young boll), buds and flowers. For Mustafa et al. (2004), one larva can damage 10 to 12 fruiting bodies in its life span. Excrements in infected buds and bolls when much are rejected out of the organ (figure 5). In some cases (2nd generation of infestation and in shortage of fruiting organs), the caterpillars can attack young leaves and branches.

On conventional cotton (non-Bt varieties), larval feeding can result in: seedlings being tipped out, chewing damage to squares and small bolls causing them to shed, and chewed holes in maturing bolls, preventing normal development and encouraging boll rot (Leven et al. 2010).

In China, the first generation of *H.A.* occurs in wheat fields; the second generation usually damages the cotton tips, the third generation feeds on squares, and the fourth generation causes damage to cotton bolls, because few flower buds and cotton tips have been removed at this time (Men et al. 2005).

Figure 5: *Helicoverpa armigera* feeding on a cotton boll
Source : HYPPZ - Hypermédia pour la protection des plantes - Zoologie

In Burkina Faso, *Helicoverpa armigera* breeds in two types of asynchronous agrosystems (Nibouche 1994): During the rainy season, from mid-June to October, the pest colonizes rainfed crops (mainly cotton and maize) and weeds. Throughout the dry season, from October to mid-April, *Helicoverpa armigera* attacks irrigated crops.

The life cycle of *Helicoverpa armigera* is completed in four stages: egg, larva, pupa and adult (figure 6). Lammers et MacLeod (2007) reported that a female may lay up to 3000 eggs (more than 400 in 24 h), mainly at night. Feng et al. (2004, 2005a, 2005b, 2009) reported that moths can travel about 250km per night in the maximum duration of flight between 7 and 8 h. A wide host range; a high fecundity; a facultative diapauses; a capacity to migrate; and the ability to develop high resistance to insecticides have enabled this insect to survive in various habitats, to adapt to seasonal changes, and thus to attain key pest status among various major crop pests (Nibouche *et al*., 1998; Kumar *et al*., 2009; Ratna *et al.,* 2012).

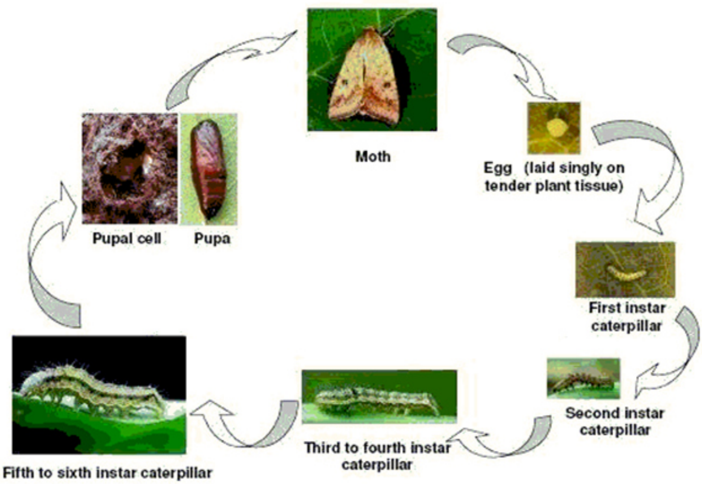

Figure 6: Life cycle of *Helicoverpa armigera*
Source: modified from *Varela, (2011)*

Helicoverpa (=Heliothis) armigera is currently placed on Annex I A II of Council Directive 2000/29/EC, indicating that it is considered to be relevant for the entire EU and that phytosanitary measures are required when it is found on any plants or plant products (Lammers and MacLeod, 2007).

The global distribution of *Helicoverpa armigera* is shown in Figure 7. The pest is present and widespread in Asia, Africa and Oceania. Given the current pest status in Europe, *Helicoverpa armigera* is established in the following EU Member States: Bulgaria, Greece, Portugal, Romania, Spain (widespread) and Cyprus, France, Hungary and Italy (restricted distribution).

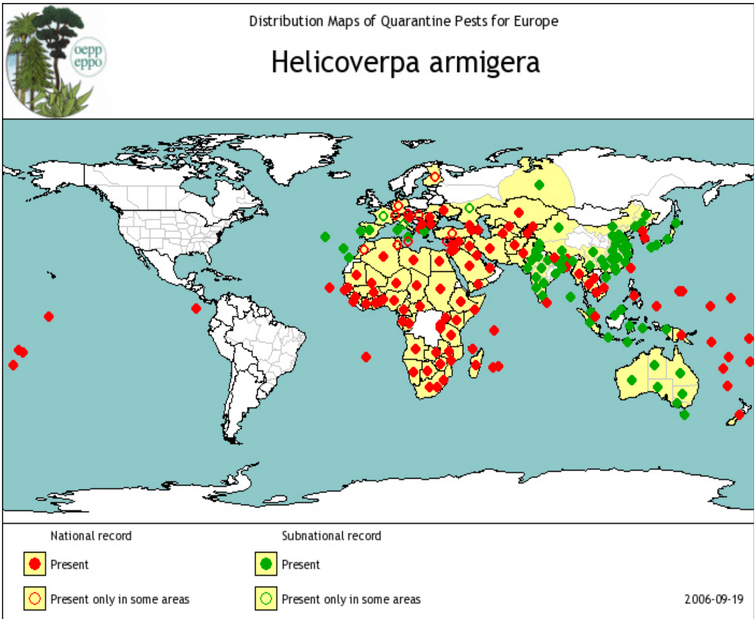

Figure 7: Distribution map of *Helicoverpa armigera* in the world
Source: Lammers and MacLeod, 2007

2.3. Short review of Helicovepa Armigera control methods

Different control methods of the cotton boll worm are well described by Shahid (2000) and Traore (2008). Some of them are:

2.3.1. Varietal control

Varietal control method requires the choice of a cotton variety according to the target pest. The cotton variety may be natural or genetically modified. The genetically modified cotton is grown mostly against the cotton boll worm.

2.3.2. Agronomic control

Agronomic control of cotton plant pests includes the whole range of farming techniques used to disturb the development of pests at a given stage of their biological cycle. These techniques run all the way from preparing the field to performing post-harvest operations. Some examples are:

- Early sowing

  Early sowing as soon as the rains have begun can avoid the coincidence of the most sensitive period of the cotton plant and the second or third generation of *H.A.* larval stage which is the most dangerous to the plant.

- Plowing

  Deep plowing will bring the pupal stage of the pests to the surface before emergence. These pupae are either collected by birds or dried out by the climate, thus diminishing the number of butterflies to emerge.

2.3.3. Biological control

Biological control of *Helicoverpa armigera* could be achieved with the following predators: *Trichogramma chilonis, Chrysoperla carnea, Coccinellids* (Kumar et al. 2009).

2.3.4. Organic control

The organic control requires the use of organic insecticides. Some of them are made of *Hyptis spicigera*, *Azadirachta indica* and *Euphorbia balsamifera* and results are encouraging (Bambara and Tiemtoré 2008). Most of these botanical pesticides are nonselective poisons that target a broad range of pests. Botanical pesticides are biodegradable (Delvin and Zettel 1999) and their use in crop protection is a practical sustainable alternative.

2.3.5. Chemical control

The best method to struggle against the cotton boll worm until now in Burkina Faso and in many other countries is the use of chemical insecticides. Below are some strategies of the chemical control method.

- Calendar-based treatment program

The principal objective in developing a calendar-based treatment program, or predefined treatment program, was to ensure that cotton plants are protected during the entire period from the start of flowering until the majority of formed bolls have reached maturity (Bertrand et al. 2009). There are two types of this program:

  - The standard program was mostly aimed at protecting the fructiferous phase of cotton plants. The interventions began as soon as the first flowers appeared, roughly 45 to 50 days after sprouting. In general, the recommended treatment schedule was every 14 days. The number of treatments typically came to five or six. All the applications were done solely with mixtures (pyrethroid + organophosphorus) or occasionally three products (one pyrethroid + two organophosphorus) throughout the period of protection. This unvaried approach resulted in the development of resistance of *Helicoverpa armigera*.

o Windows program was motivated by the appearance and the expansion of the problem of resistance to pyrethroids of *Helicoverpa armigera*. Two and three windows program are distinguished:

- Two-windows program: This program is based on the principle that the first and second treatments form the first window, while the second window consists of the remaining four (third, fourth, fifth, and sixth treatments).

- Three-windows program: The first and second treatments form the first window; the third and fourth treatments form the second window; and the fifth and sixth treatments form the third window. It is important to note that the choice of products to be applied is made with great care. Thus:

For both types of window program, the treatments of the first window are always performed with a product that does not belong to the pyrethroid family, as the objective is to reduce the duration of use of the molecules of this family, to which *Helicoverpa armigera* has developed a resistance. A few examples include Profenofos, Indoxacarb, Spinosad, Malathion, Flubendiamide-spirotetramate association, etc.

During the second window (two-window program) or the last two windows (three-window program), the treatments are performed with binary products containing a pyrethroid in association with a product from a different family.

In the case of the three-window program, the second window may involve the use of acaricides, followed by aphicides and/or aleurodicides during the third window. Examples of such products include:

- acaricides: Cypermethrine/Profenofos, Deltamethrine/Triazophos
- aphicides/aleurodicides: Lambdacyhalothrine/Acetamiprid, Alphamethrine/Imidacloprid

This new strategy has been widely adopted in the subregion of West Africa. It has helped reduce the growing problem of caterpillar resistance to pyrethroids. In addition, it has led to greater awareness in regard to the necessity of avoiding the emergence of the same problem with other cotton crop pests.

- Threshold-based program

Two types of threshold-based pest control schemes for cotton have been introduced by CIRAD, in collaboration with national research institutions in West Africa, to escape the traditional calendar-based spraying program (Silvie et al. 2001). In the first type, insecticides are still applied according to a calendar (6 or 5 sprayings at fortnightly intervals), but formulations and dosage depend on the pest observed on the day before spraying. In the second type, insecticides are applied at a lower dosage than in the usual calendar-based program and scouting is performed 6 days after spraying. Sampling methods and the choice of economic threshold are described in the technical sheets (1 to 4) of Nibouche et al (2002 a, b, c and d).

These control methods have tremendously contributed in cotton growing. Most of them are still in practice and the best until now is the chemical control. But these methods still suffer some insufficiency related to the cost of implementation and environmental issues. In order to cover the gap, **control theory will be applied in this study to enhance crop yield in agriculture through pest management by pesticides with respect to the environment. Mathematical models and simulations will guide to this end**.

2.3.6. Adaptive control

The need for accurate timing and application dose of pesticides spraying leads to the concept "adaptive control". Adaptive control is a specific type of control, applicable to processes with changing dynamics in normal operating conditions subjected to stochastic disturbances. It is a specific type of control where the process is controlled in a closed-loop, and where knowledge about the system characteristics is obtained while the system is operating (Zoran 2000). Based upon refreshed information obtained during normal operation, specific interventions in the control loop are made in order to fulfill the control goal.

The control goal in the present situation is to uphold the pest population density under a given threshold which may be the economic threshold. Interventions are made when the pest population density exceeds the threshold.

The control design task is to choose the input application scheme so that the output response (the gain) satisfies the given performance requirement which is: maximize the gain!

Below (figure 8) is presented the control structure implemented in the computer program developed for this purpose. First, the program controls the pest population density data at day d, and then compares the data with the threshold. If the population density exceeds the threshold, then an initial dose (reference dose) will be requested. If there is a need for another input, it will be implemented automatically from the initial dose under some rules that will be specified later in paragraph 3.11.3 of this thesis.

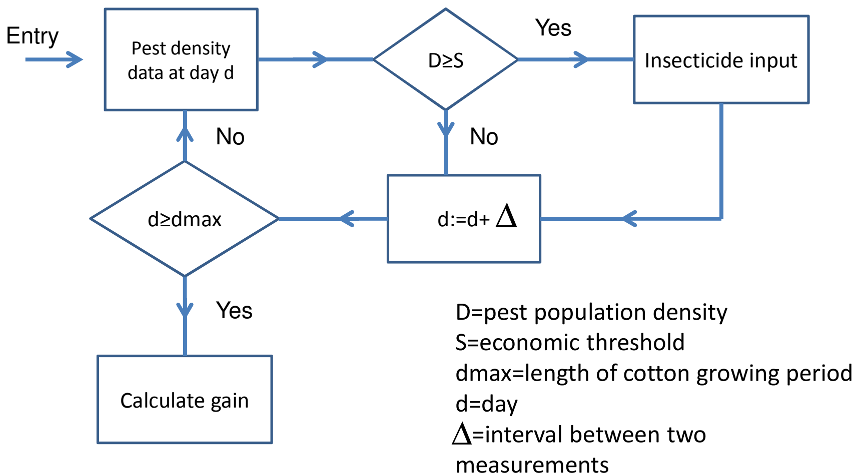

Figure 8: Adaptive control structure implemented in the computer program

2.3.7. Optimal control

As defined in Bangert (2012), suppose we have a function *f(x)* where the variable *x* may be a vector of any dimensions. Optimization is seeking the point *x** such that *f(x*)* is the maximum (or minimum) value among all possible *f(x)*. This point *x** is called the global optimum of the function *f(x)*. It is possible that *x** is a unique point but it is also possible that there are several points that share the maximal (minimal) value of *f(x*)*.

Cohen (1986) applied optimal control theory in ecology to investigate the conditions under which an annual plant exhibits two distinct reproductive strategies which result in maximum fitness by the end of a fixed-length growing season.

We will investigate in our study the optimal insecticide application scheme $AS = \{(t_1, D_1), \ldots, (t_n, D_n)\}$, that is the optimal allocation of insecticide application dose $D_{i(i=1,\ldots,n)}$ at the optimal time $t_{i(i=1,\ldots,n)}$ which maximizes the objective function that will be developed later in paragraph 3.11.4 of this thesis.

3. Model development; DSS development

The overall model development is resumed in the compartmental model described by figure 9. The crop (cotton bolls) is consumed by the pest (*Helicoverpa armigera*) which is stressed by insecticides when applied. Applied insecticides probably accumulate in the environment and particularly in water resources in our case. The models are developed establishing mass balance equations for this ecosystem (figure 9).

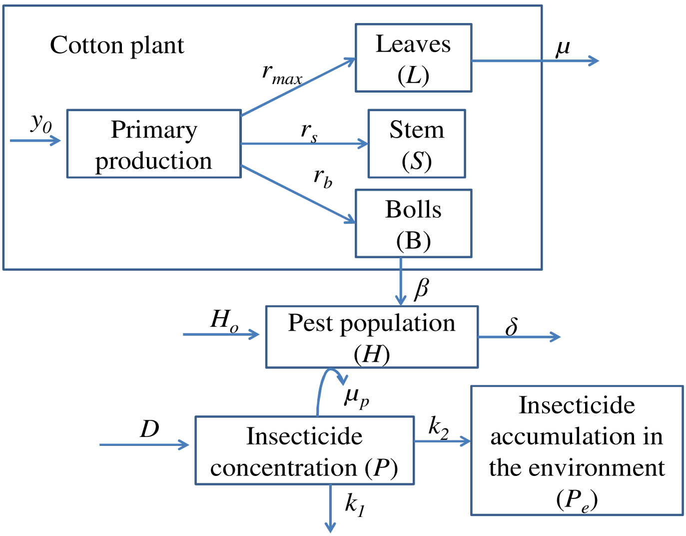

Figure 9: Compartmental model consisting of crop, pest and the concentration of insecticide

3.1. Crop growth model (cotton crop)

Plant growth models have been developed for decades of years. They are considered as useful tools to investigate plant growth behavior and are considered as complementary tools to experiments.

Classical growth models as described in Richter and Söndgerath (1990) for one organ or for a whole organism are derived from a differential equation of the general form:

$$\frac{dW}{dt} = r * W * \Phi(W) \qquad (1)$$

With the initial condition $W(t=0) = W_0 > 0$. W denotes the biomass and r a growth rate. The function $\Phi(W)$ is a monotonically decreasing function of W, which is denoted as resistance against growth.
$\Phi(W)$ has the following properties:

- $\lim_{W \to 0} W\Phi(W) = 0$
- there exists a constant $K > 0$ such that

$$\Phi(W) \begin{cases} > 0 & if \quad W < K \\ = 0 & if \quad W = K \\ < 0 & if \quad W > K \end{cases}$$

With these properties, the growth curve has a sigmoid shape.

Since leaves are essential for the whole plant growth including all organs, the starting point is a mass balance equation for leaves biomass (2). The growth of all other organs is closely related to photosynthetic activity within leaves, which is in turn a function of leaves biomass. If overlapping of leaves is negligible, i.e. if leaf area index is less than one, growth rates are directly proportional to leaf biomass. The partition of assimilates follows a certain temporal pattern. This pattern can be generated by use of explicitly time dependent control functions $f_j(t)$ and by state dependent control functions ψ_j.

The index L refers to leaf in equation 2:

$$\frac{dy_L}{dt} = r_L \Phi_L(y_L)\psi_L(\cdots)f_L(t)y_L - \mu_L y_L \qquad (2)$$

The differential equations for all other organs take the form:

$$\frac{dy_j}{dt} = r_j \Phi_j(y_j)\psi_j(\cdots)f_j(t)y_L - \mu_j y_j \qquad for \quad j \neq L \qquad (3)$$

For cotton plant, numerous models have been developed and each for a particular purpose. For example:

Wall et al. (1994) developed the cotton simulation model COTCO2 for cotton response to atmospheric CO_2 concentration;

Zhang et al. (2008) Developed SUCROS-Cotton with a particular attention to the phenological development of the plant and the plasticity of fruit growth in response to temperature, radiation, daylength, variety traits, and management;

Liang et al. (2012a and b) developed a geographically distributed cotton growth model from the original GOSSYM and optimized it for coupling with the regional Climate-Weather Research Forecasting model

(CWRF). GOSSYM predicts crop growth (with detailed plant chemistry, morphogenesis, and phenology) and soil responses to environmental stresses, primarily from heat, water, carbon, and nutrients;

Yang et al. (2008b) reported that COTTON2K V4.0 is a process based model that can simulate soil and plant processes as influenced by meteorological conditions and field management practices.

The cotton growth model we developed is a simple descriptive model, not simulating physiological behaviors but offering many advantages such as:

→ contains only few parameters. The increased number of parameters in the models with a time-varying coefficient makes them more difficult to fit (Adams et al. 2005),

→ applicable to a large class of plant growth,

→ parameter estimation problem does not pose any difficulties regarding both numerical aspects and experimental design.

The cotton plant develops in three main organs. We develop the model for cotton dynamics as follow.

- Equation for cotton leaves development

Growth of leaves starts at the beginning of the vegetation period triggered by temperature (or by day length as in Europe for example) and stops according to an intrinsic “clock” and to external environmental variables such as temperature.

By assuming in equation (2) that $\Phi = \psi = 1$, the ordinary differential equation (ODE) for the development of cotton leaves is derived (4).

$$\frac{dL}{dt} = f_s r_{\max} L - \mu L \tag{4}$$

with the initial condition $L\ (t=0) = L_0 > 0$.

The temporal pattern is governed by the control function $f_s(t)$ named senescence function which starts with its maximum value and decreases in a sigmoid manner (figure 10) with the positive parameters a and b,

$$f_s(t) = (1+a)\frac{e^{(-b(t-t_{min}))}}{1+ae^{(-b(t-t_{min}))}} \tag{5}$$

$f_s(t)$ has the following properties:

$$f_s(t) \geq 0$$
$$\lim_{t\to\infty} f_s(t) = 0$$

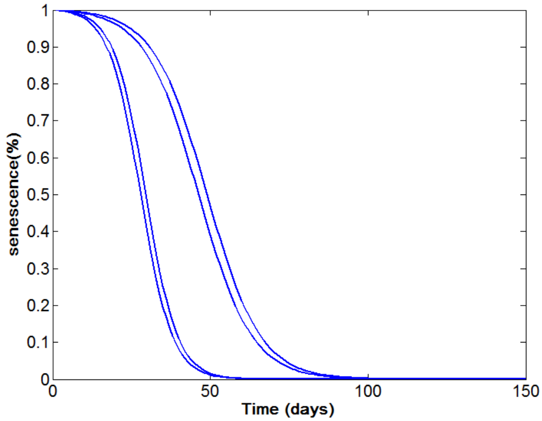

Figure 10: Senescence function for different values of a and b. From left to right, a=217, b=0.119; a=300, b=0.119; a=217, b=0.2; a=300, b=0.2

The growth of all other organs is closely related to photosynthetic activity within leaves, which is in turn a function of leaves biomass. Equations for stem and boll are then derived as follow.

- Equation for cotton stem development

The differential equation for stem development (6) was developed with the idea of logistic growth. *S* is the stem biomass density, r_s the stem growth rate and K_s the field carrying capacity for stem biomass. The term in brackets is the retardation factor limiting to K_s the maximum attainable biomass on the field for stem.

$$\frac{dS}{dt} = r_s L\left(1 - \frac{S}{K_s}\right) \tag{6}$$

With the initial condition $S(t=0)=S_0 \geq 0$

- Equation for cotton bolls development

The differential equation for boll development (7) was developed with the idea of logistic growth. *B* is the boll biomass density, r_b the boll growth rate and K_b the field carrying capacity for boll biomass. Boll development starts when a critical time t_s is reached, after the beginning of the development of leaves and stem, with a smooth transition. This pattern is governed by the time dependent switching function $f_b(t)$ (8) (figure 11). t_s and α are positive fitting parameters.

$$\frac{dB}{dt} = f_b r_b L\left(1 - \frac{B}{K_b}\right) \tag{7}$$

With the initial condition $B(t=0)=B_0 \geq 0$

$$f_b = 1 - e^{-\left(\frac{t - t_{min}}{t_s}\right)^{\alpha}} \tag{8}$$

The switching function depends on two positive parameters, the switching time t_s and the smoothness of the transition α.

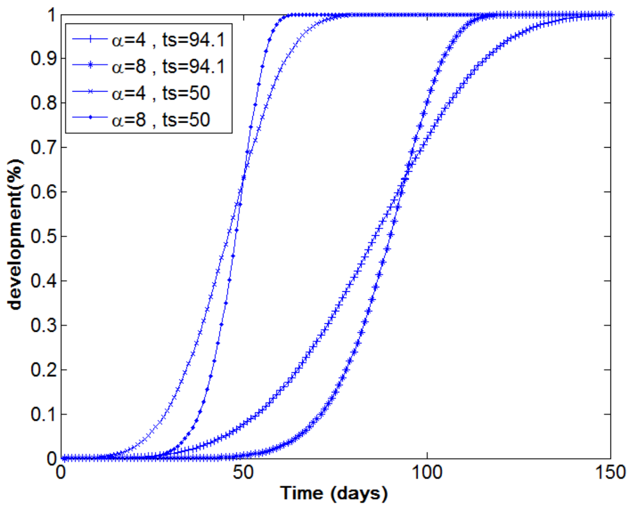

Figure 11: Switching function for different values of α and t_s

Remark: the control functions could also be step functions or of various other forms. In the course of model development, many possible approaches were tried out and only the forms described above were retained, which lead to a satisfying fit to the data with a minimal number of parameters as described in the following parameters estimation section.

3.2. Example of application for the crop growth model

3.2.1. Parameters estimation for cotton growth model

Based on literature data, parameters for cotton growth model could be estimated. The data used was selected among many others from the internet and from some publications and books. The selection criterion was the accuracy and the relevance of the information. The cotton growth data we used for parameters estimation come from the software DSSAT (Hoogenboom et al. 2012) version 4.5. Data courtesy of Gerrit Hoogenboom.

The system of ODEs (equations (4), (6) and (7)) form a dynamic system with parameters μ, r_{max}, r_s, r_b, a, K_s, K_b, α, t_s, and b to be estimated. We proceeded as follow: At n time points $t_1, t_2, \ldots, t_n$, density data $L_1, L_2, \ldots, L_n$; $S_1, S_2, \ldots, S_n$ and $B_1, B_2, \ldots, B_n$ for cotton leaves, stem and bolls respectively are obtained from field or experiment. The mathematical problem is to find a parameter vector $\theta = (\mu, r_{max}, r_s, r_b, a, K_s, K_b, \alpha, t_s, b)'$ which minimizes the performance criterion here the least squares criterion or the cost function given by equation (9).

$$G(\theta) = \sum_{j=1}^{n} \left[\left(L(t_j, \theta) - L_j \right)^2 + \left(S(t_j, \theta) - S_j \right)^2 + \left(B(t_j, \theta) - B_j \right)^2 \right] \qquad (9)$$

The least squares estimator defined by equation (10)

$$G(\hat{\theta}) = min[G(\theta)] \qquad \theta \in U \qquad (10)$$

U denotes the space of admissible parameters. Thus **a nonlinear regression problem involving ordinary differential equations (ODE) for parameters estimation is to be solved**. Because the solution can only be attained approximately by numerical methods, the regression problem is implicit. The set U is derived both from the physical (biological) and the mathematical point of view. Sometimes it is feasible to experimentally measure physical parameters but in many cases the measurement is very hard, expensive, time consuming or even impossible.

For the evaluation of $G(\theta)$, the solutions of the differential equation dynamic system has to be known.
Hence, two numerical problems are involved in parameter estimation:

- In addition to the problem of minimizing the sum of squares (or whatever criterion measure is chosen) differential equations have to be solved numerically.
- Both tasks have to be accomplished simultaneously: numerical solutions algorithms for ordinary differential equations have to be embedded into minimization algorithms.

The computation yielded the estimates recorded in table 1 and Figure 12 shows the fitted curves. The ODEs are solved by invoking the Matlab ODE solver ode45, an adaptive explicit Runge-Kutta solver. Matlab's non linear least square solver lsqnonlin was invoked for parameter estimation. The algorithm lsqnonlin is a Gauss-Newton method which switches to Levenberg-Marquardt when parameter step sizes are small.

Table 1: Parameters estimates for the cotton growth model

Parameter	Estimated value	Unit
μ	0.000881	1/day
r_{max}	0.428	1/day
r_s	0.051	1/day
a	188	-
r_b	1.06	1/day
K_s	3660	Kg/ha
K_b	6190	Kg/ha
α	4	-
t_s	92.2	days
b	0.428	-

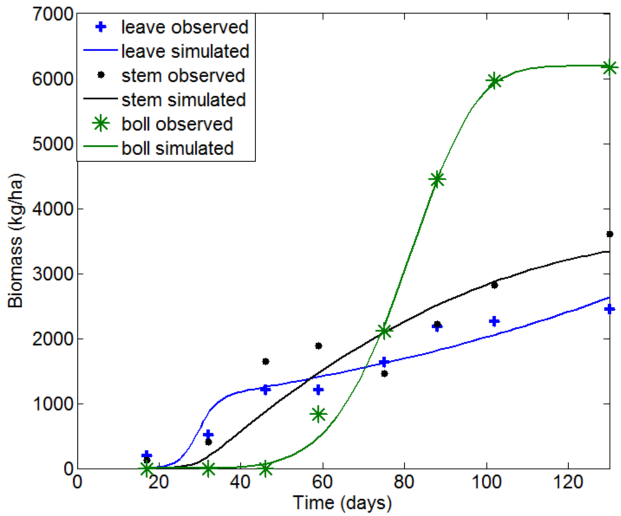

Figure 12: Cotton growth simulation model fit to data

3.2.2. Performance Criteria of the Estimates

To determine an estimator, we need a set of criteria by which its performance can be judged, dependent on the purpose for which the estimator is obtained. We judge the performance of the estimates via the model residual analysis and the Nashs Sutcliffe factor of model efficiency.

3.2.2.1. Residual analysis

To evaluate the adequacy of the model itself relative to the data (and assumptions), residual analysis are performed.

Definition: The residuals from a fitted model are the differences between the responses observed at each combination values of the explanatory variables and the corresponding prediction of the response computed using the regression function. Mathematically, the definition of the residual for the i^{th} observation in the data set is written

$e_i = y_i - f\left(\vec{x}_i ; \hat{\vec{\beta}}\right)$ *, with y_i denoting the i^{th} response in the data set, $\vec{x}_i$ represents the list of explanatory variables, each set at the corresponding values found in the i^{th} observation in the data set and $\hat{\vec{\beta}}$ represents the list of estimated parameters.*

The scatter plots of the residuals (figure 13) is disordered and do not show any trend suggesting that the errors are independent and have a constant variance. This indicates that the model does not exhibits systematic deviations.

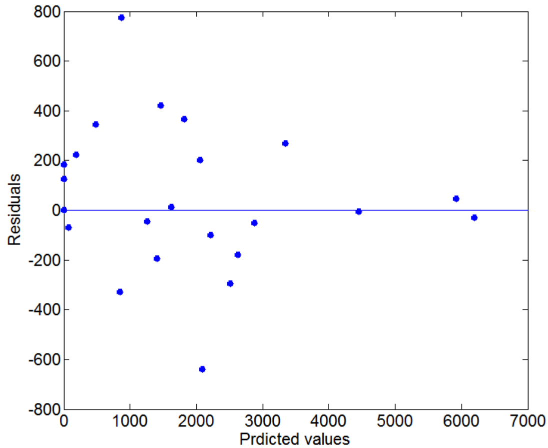

Figure 13: Scatter plot of residuals

3.2.2.2. Model efficiency

The performance measure of the fit was estimated via the Nashs Sutcliffe factor of model efficiency:

$$M_f = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{11}$$

With O observed and P predicted values.

The Nash-Sutcliffe efficiency is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe 1970). It indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al. 2007). The range of M_f lies between 1 (perfect fit) and $-\infty$. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model.

The value obtained for the cotton growth model is $M_f = 0.87$ indicating a very good fit of the model with the data.

Krause et al. (2005) and Janssen and Heuberger (1995) discussed more methods for performance measurements for comparing model predictions and observations.

3.3. Pest population (H.A.) dynamics in interaction with crop (cotton crop) dynamics

Population models have been developed for *Helicoverpa zea* (Boddie) in North Carolina and *Helicoverpa zea* and *Heliothis virescens* (Fabricius) in Texas. According to Holt et al (1990), these models are complex and detailed representations of particular cropping systems in which many of the relationships are specific to the particular location and cropping system. Holt et al (1990) described a simulation model for the population dynamics of *H.A*. (Hübner) on pigeonpea *Cajanus cajan* (L.) Millsp., in southern India with the life cycle processes controlled by a set of simple transfer functions.

We propose two models for the simulation of the population dynamics of the pest *H.A.* and its impact on cotton crop. The first is a continuous time model in the form ODEs and the second is a discrete time matrix model.

- **Time continuous pest population dynamics model in interaction with crop dynamics**

The larvae of *H.A.* feed on cotton bolls. We assume that cotton bolls are consumed by the pest employing a consumption rate of the Michaelis-Menten type because of its saturation behavior. Equation (7) then becomes equation (12). The consumption of the biomass is described by the second term of equation (12) where β is the maximal consumption rate and K_B the saturation constant.

$$\frac{dB}{dt} = f_b r_b L\left(1 - \frac{B}{K_b}\right) - \frac{\beta BH}{B + K_B} \tag{12}$$

The time continuous population dynamic model is described by equation (13) assuming a predator-prey interaction with saturation between the pest and the crop. In this model, γ is the efficiency factor, H the pest density (*H.A.* larvae density) and the mortality process is modeled by first order kinetics with μ_H the natural mortality rate.

$$\frac{dH}{dt} = \frac{\gamma BH}{B + K_B} - \mu_H H \tag{13}$$

Pest outbreak usually starts when the biomass is present on the field. In this way, there is a time laps between the beginning of crop development and the appearance of pest. The initial condition for pest is therefore $H(t=t_0>0)=H_0$.

3.3.1. Example of application of crop-pest interaction with continuous time model

Data of Twine (1978) on the consumption of fresh matter by each larval instar of *H.A.*, reported in Nibouche et al. (2007) were used to estimate parameters β and K_B. We fitted (figure 14) the data to the second term of equation (12) and obtained β = 991.9 mg/day and K_B = 2516mg with the Nash-Sutcliffe efficiency factor of 0.99. Following the study of Mustafa et al. (2004), the mortality of first instar larvae was 29.54%. We used this value for δ_H in our model.

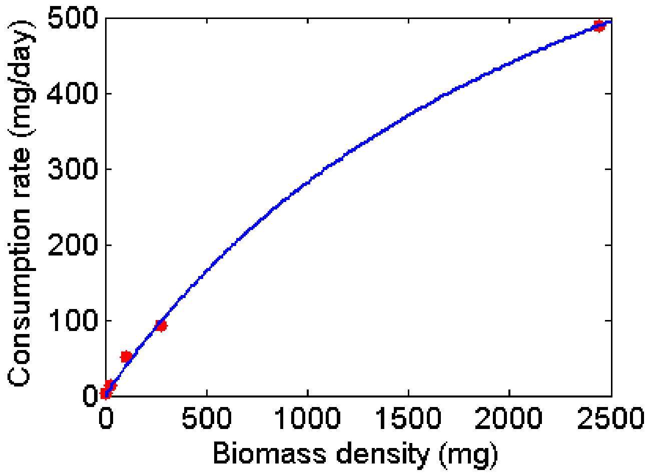

Figure 14: Biomass consumption rate of *Helicoverpa armigera*

We started the simulation with 1000 pests individuals (*H.A.* larvae) emerged on day 30 after crop planting. In figure 15b, the crop continues to grow for a while after the outbreak of the pest (figure 15a) without any visible effect. When the pest population density reaches a certain amount, the impact on crop increases and the damage becomes significant in time. These observations imply the existence of a threshold of the pest population density above which crop damage is considered to be significant. These are indications that the model has a very good behavior.

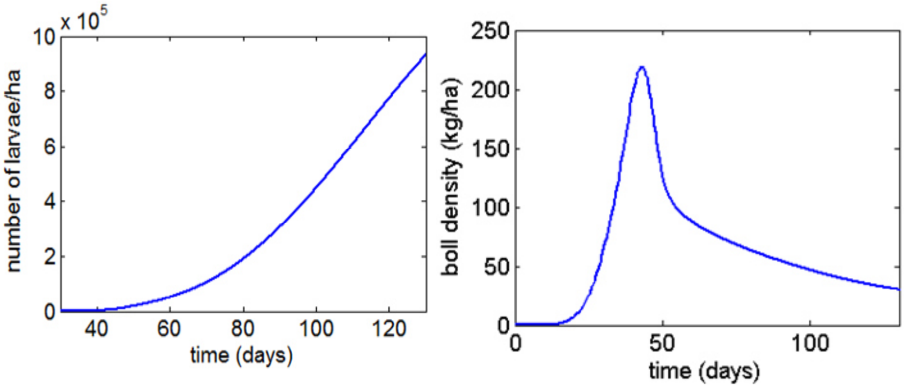

Figure 15: Larvae population dynamics in interaction with cotton bolls dynamics without pest control measure (e.g. insecticides application). (a) larvae dynamics; (b) cotton bolls dynamics

3.4. Time discrete pest population dynamics modeling

A time discrete matrix model can be used to simulate the temporal dynamics of *H.A*. Matrix models are used to describe the dynamic of populations classified by age or other criteria like size or stage (Söndgerath 2011).The pest *helicoverpa armigera* has a life cycle development of four stages: egg, pupae, larva and adult. The Leslie matrix model is a special case of discrete time model where a population is divided into age classes of the same length as the time step. Since the population dynamics of *H.A*. presents age and stage structure, the extended Leslie model combining both structures we employed here is suitable to investigate the dynamic of *H.A*. The extended Leslie model was developed by Söndgerath and Richter (1990). A thorough description of this model can be found in the book of Richter and Söndgerath (1990). Matrix population models offer the advantage of simplicity in the modeling process of underlying biological phenomena and in the simulation running. The extended Leslie model had been used to simulate the population dynamics of *Scolothrips longicornis* Pristner (Söndgerath and Richter 1990) and cabbage root fly (Delia radicum L.) (Söndgerath and Müller-Pietralla 1996) and yielded plausible results.

Let there be $s=1,\ldots,n$ stages with $i=1,\ldots,m_s$ age classes.

The following notations are used:

$x_{si}(t)$ = expected number of individuals in age class i of stage s at time t $(t=1,2,\ldots)$;

P_{si} = probability of surviving from age class i of stage s to age class $(i+1)$ of the same stage;

F_i = expected number of offspring per individual in age class i of stage n;

$U_{si}(t)$ = probability of transition from age class i of stage s to age class 1 of stage $(s+1)$ at time t.

The model equations are deduced as follows.

The individuals in age class i of stage s at time $t+1$ are those surviving from age class i at time t and not developing to individuals of stage $s+1$.

$$x_{s,i+1}(t+1) = (1 - U_{si}(t))P_{si}x_{si}(t) \quad \text{for} \quad i = 1,\ldots,m_s - 2 \quad \text{and} \quad s = 1,\ldots n \tag{14}$$

It is assumed that all individuals surviving the last age class of any stage are collected in this age class.

$$x_{s,m_s}(t+1) = (1 - U_{s,m_s-1}(t))P_{s,m_s-1}x_{s,m_s-1}(t) + (1 - U_{s,m_s}(t))P_{s,m_s}x_{s,m_s}(t) \quad \text{for} \quad s = 1,\ldots n \tag{15}$$

The first age class of a stage *s=1,…,n* is composed of those individuals of stage *s-1* developing to individuals of the next stage s at time t.

$$x_{s1}(t+1) = \sum_{i=1}^{m_{s-1}} U_{s-1,i}(t)x_{s-1,i}(t) \quad \text{for} \quad s = 2,\ldots,n \tag{16}$$

For the first age class of the first stage the fertility coefficients have to be taken into account.

$$x_{11}(t+1) = \sum_{i=1}^{m_n} U_{ni}(t)F_i x_{ni}(t) \tag{17}$$

Figure 16 explains these equations graphically.

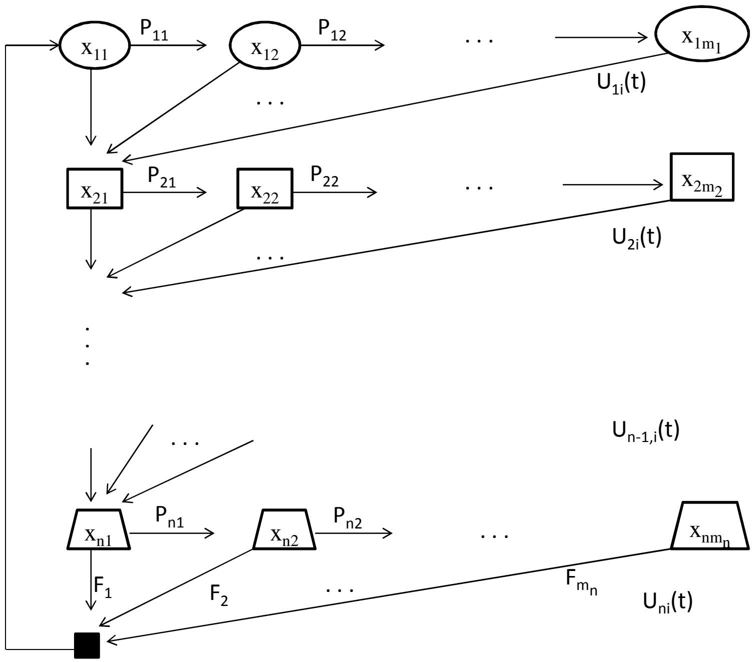

Figure 16: The extended Leslie model for populations with n development stages ($s=1,\ldots,n$), each with m_s age classes ($i=1,\ldots,m_s$)

Employing matrix notation with $x(t)=\left[x_{11}(t),\ldots,x_{n,m_n}(t)\right]'$ and an appropriate M_t, these equations become

$$x(t+1)=M_t x(t) \tag{18}$$

The matrix M_t is time-dependent in consequence of the time dependence of the transition probabilities. The matrix is composed of two kinds of sub matrices, one with non-zero elements in the first row

(L_{st}) and the other with non-zero elements only in the first subdiagonal (K_{st}).

$$K_{st} = \begin{pmatrix} 0 & 0 & \cdots & 0 & 0 \\ a_{st1} & 0 & \cdots & 0 & 0 \\ 0 & a_{st2} & 0 & \cdots & 0 \\ \vdots & & & & \vdots \\ 0 & \cdots & 0 & a_{st,m_s-1} & a_{st,m_s} \end{pmatrix} \quad with \;\; a_{stj} = \left(1 - U_{sj}(t)\right) P_{sj} \quad for\, j = 1, \cdots, m_s$$

$$L_{st} \equiv \begin{pmatrix} U_{s1}(t) F_{s1} & \cdots & U_{s,m_s}(t) F_{s,m_s} \\ 0 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & 0 \end{pmatrix}$$

With the convention that $F_{si}=1$ for $s=1,\ldots, n-1$ and $F_{ni}=F_i$, the matrix M_t is written as:

$$M_t = \begin{pmatrix} K_{1t} & 0 & \cdots & 0 & L_{nt} \\ L_{1t} & K_{2t} & 0 & \cdots & 0 \\ 0 & L_{2t} & K_{3t} & \cdots & 0 \\ \vdots & & & & \vdots \\ 0 & \cdots & 0 & L_{n-1,t} & K_{nt} \end{pmatrix}$$

3.4.1. Example of application for the time discrete population model (*H.A.*)

Temperature is considered as the major abiotic factor which has a profound effect on distribution, colonization, survival, abundance, behaviour, fitness and the life history of insects in general (Howe 1967, Nibouche 1998, Ahumada et al. 2004, Yamamura et al. 2006, Liu et al. 2010, Mironidis and Savopoulou-Soultani 2010). Liu et al. (2004) evaluated in laboratory under a constant temperature (27°C) the development, body weight, survivorship, and reproduction of the cotton bollworm *H.A.* (Hübner) on six host plants among which the cotton plant. Seven larval instars were evaluated. Other laboratory studies were conducted by Mironidis and Savopoulou-Soultani (2008), to assess the effect of temperature on the survival, development, fecundity, and longevity of *H.A.* (Hübner) at 11 constant temperatures ranging from 12.5 to 40°C and alternating temperatures. We used their alternating temperatures data ranging from 35°C to 27.5°C (tables 2 and 3).

Table 2: Survivorship (percentage) of immature stage of *H.A.* reared under alternative temperatures ranging from 35°C to 27.5°C.

	Larval instars					
Egg stage	First	Second	Third	Fourth	Fifth	Pupal stage
56.55	70.11	90.16	96.36	98.11	96.15	89.58

(Mironidis and Savopoulou-Soultani, 2008)

Table 3: Mean development time (days ± SE) of immature stages of *H.A.* under alternating temperatures ranging from 35°C to 27°C

	Larval instars					
Egg stage	First	Second	Third	Fourth	Fifth	Pupal stage
2.08 ±0.01	2.13 ±0.08	1.53 ±0.07	2.19 ±0.18	3.30 ±0.32	4.64 ±0.27	8.79 ±0.13

(Mironidis and Savopoulou-Soultani, 2008)

In their study adult females' longevity was found to be 14.11±1.73 with an average oviposition rate of 26.18±2.15 eggs per day.

We used integer values for application at a daily time step, under alternating temperatures ranging from 35°C to 27.5°C. The model was run for 130 days (figure 17) with the following initial population: 0 eggs, 1000 larvae, 0 pupae and 0 adults.

Peaks (figure 17) in the curve can explain the generations in the dynamics of the population. It can be thought of the overlapping of the population of *H.A.* (Gupta et al. 2003) because the pest never vanishes in at least one life stage within the simulation period. The larvae density increases when the egg density decreases, indicating the hatching of eggs. In the same sense, the pupae density increases slowly with the decrease of larvae. These are larvae going into the pupal stage. The emergence of adults is synchronized with the decrease in pupae population. These observations suggest a very good behavior of the model.

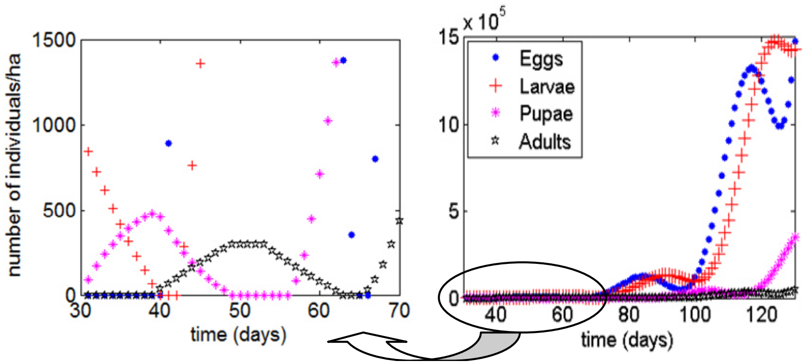

Figure 17: Dynamics of *helicoverpa harmigera* in the absence of control measure (e.g. insecticide application). Pest invasions start on day 30 after planting

- **Time discrete pest population dynamics model in interaction with crop dynamics**

Since we are interested in the consumption of cotton bolls by the larval stage of the pest, the pest density *H(t)* in equation (12) for crop-pest interactions is the total sum of larvae from all the larval age classes at time *t*. Both models are coupled to each other and computed as a sequence of initial value problem.

In the beginning, the crop grows normally until the pest emergence (figure 18). Because the pest density is not yet enough to cause substantial damage, the crop continues to develop until the pest reaches the density susceptible to cause significant damage, indicated by the first decrease in the curve. Because the cotton plant has the ability to recover its losses (Poveda et al. 2012, Men et al. 2005, Thomson et al. 2003) to some extent, it will grow again when the population of larvae decreases (second increase in figure 18). The oscillation in the curve (figure 18) is explained by the increase and decrease of the population of larvae as indicated in figure 17. These observations imply the existence of a threshold of the pest population density above which crop damage is considered to be significant. These are indications that the model has a very good behavior.

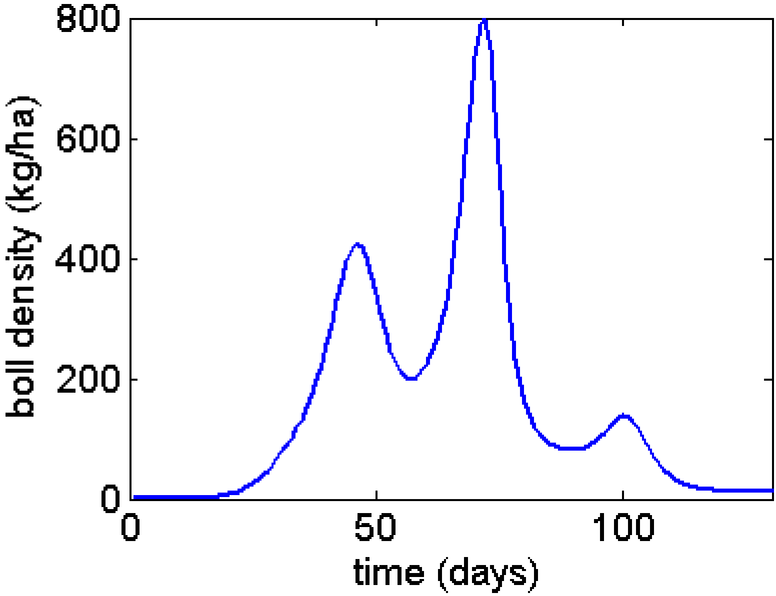

Figure 18: Crop (cotton boll) dynamics response to pest population of figure 17

3.5. Pesticides application

Dirac delta function (19) is employed to assign the input insecticide dose D_i at time t_i ($i=1,2,\ldots,n$) as punctual events which is approximated by a Gaussian type density distribution with small values of σ:

$$\delta(t-t_i)=\lim_{\sigma\to 0}\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(t-t_i)^2}{2\sigma^2}}\right) \tag{19}$$

Total pesticide input is thus represented by the superposition of single inputs (20). The profile of the curve is shown on figure 19 for a value of σ and different values of D_i and t_i.

$$D_s(t) = \sum_{i=1}^{n} D_i \delta(t - t_i) \tag{20}$$

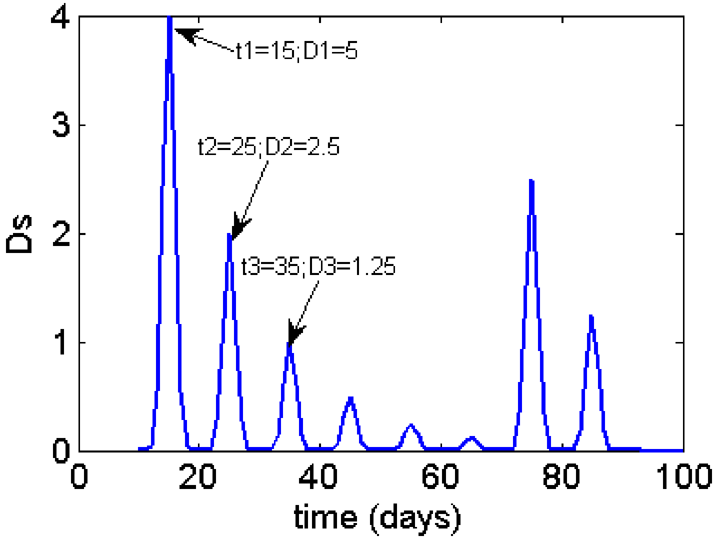

Figure 19: Profile of a dosage scheme with σ=*1*. The peaks are the inputs events

The method of optimal impulse control is particularly appropriate for analysis and modeling of many biological processes during which there is a sudden switch from a particular level of the states to another (Cohen 1986).

Equation (21) below describes the evolution in time of the total concentration of the applied insecticide with the consideration that insecticide concentration decays linearly with a rate constant k_1 and is lost to the environment with a rate k_2, where it accumulates according to equation (22).

$$\frac{dP}{dt} = D_s(t) - (k_1 + k_2)P \qquad (21)$$

With the initial condition $P(t=0)=P_0 \geq 0$

$$\frac{dP_e}{dt} = k_2 P \qquad (22)$$

With the initial condition $P_e(t=0)=P_{e0} \geq 0$

k_1 is related to DT_{50} by: $k_1 = ln\,2 / DT_{50}$

3.6. Effect of insecticide on pest population

The effect of insecticides on pest is expressed by a Weibull mortality function (23) for the time continuous model and by a Weibull survival (24) function for the time discrete model.

$$R_{cont}(P) = 1 - e^{-\left(\frac{P}{t_{hr}}\right)^{\eta}} \qquad (23)$$

$$R_{dsc}(P) = e^{-\left(\frac{P}{t_{hr}}\right)^{\eta}} \qquad (24)$$

Where t_{hr} is the threshold of insecticide dose effective to the maximum of pest density. It is related to the ED_{50} value by $ED_{50} = t_{hr}\, Log(2)^{1/\eta}$ and η is a form parameter determining the slope of the survival function.

3.7. Crop-Pest-Pesticide Modeling

The pest population dynamics under insecticide pressure is described for time continuous model and for time discrete model.

3.7.1. Time continuous model

The pest population model (13) is coupled with the mortality function (23) in term (*b*) of equation (25). Term (*b*) is the decrease of pest density due to insecticides application, assuring the link between pesticide kinetics with dynamic response. μ_p is the maximum mortality rate due to insecticide.

$$\frac{dH}{dt} = \frac{\gamma BH}{B + K_B} - \mu_H H - \underbrace{\mu_p R_{cont}(\, P(\, t\,))H}_{(b)} \tag{25}$$

3.7.2. Time discrete model

In our model, insecticides are used against the larval stage of the pest. The interaction insecticides-pest is realized such that the action of insecticide occurs in the survival probabilities of the larval stage of the pest population model. It is reasonable to couple the time discrete pest population model to the survival function (24). Thus P_{si} for the larval stage becomes $P_{si}R_{dsc}$.

3.7.3. Example of application

Indoxacarb and Spinosad are the selected insecticides for simulations. These insecticides were selected among many others under the criterion of data availability.

We estimated parameters of equation (23) by fitting (figure 20) the curve to the data of Ramasubramanian and Rgupathy (2004) who conducted studies on the response of the larvae of *H.A.* to different doses of Indoxacarb and Spinosad. We obtained the estimates in table 4. The DT_{50} of Indoxacarb and Spinosad we used here is the field soil degradation and k_2 is the estimated maximum occurrence fraction of the metabolite in water medium, given in PPDB (2014).

Table 4: Estimated values t_{hr} and η of the parameters for the mortality function for Indoxacarb and Spinosad.

	t_{hr}	η	M_f	DT_{50} (days)	k_2
Indoxacarb	31.60	0.19	0.9913	20*	0.102*
Spinosad	40.73	0.32	0.9924	<1**	0.102***

The DT_{50} and k_2 values are obtained from the literature. *data from PPDB (2014); **data from López and Fernández-Bolaños (2011). ***arbitrary value. M_f is the Nash-Sutcliffe efficiency factor.

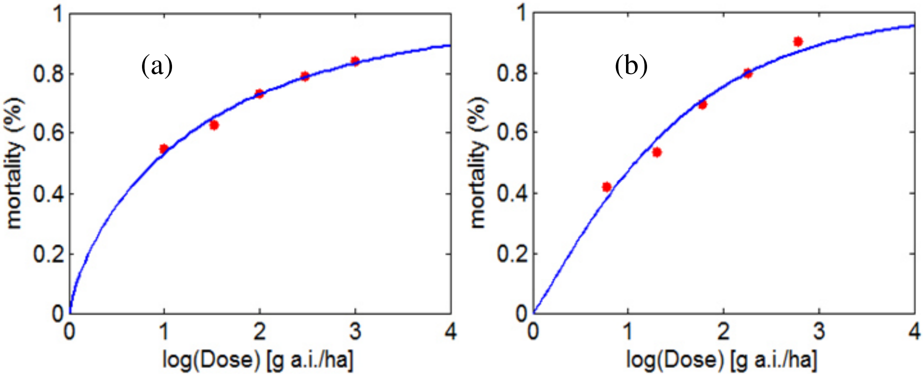

Figure 20: Dose-response curve for the effect of (a) Indoxacarb on the larval life stage of *H.A.* and (b) Spinosad on the larval life stage of *H.A.*

The recommended dose for Spinosad 60g a.i./ha for treatments against the cotton boll worm *H.A*. (Ramasubramanian and Regupathy, 2004a) was used for simulation according to the application scheme in table 6 and a dose of 10g a.i./ha was used for Indoxacab (Ramasubramanian and Regupathy, 2004b) following table 5.

Table 5: An application scheme with Indoxacarb insecticide

Dose (g a.i./ha)	10	10	10	10	10	10
Time (days after planting)	45	59	73	87	101	115

Table 6: An application scheme with Spinosad insecticide

Dose (g a.i./ha)	60	60	60	60	60	60
Time (days after planting)	45	59	73	87	101	115

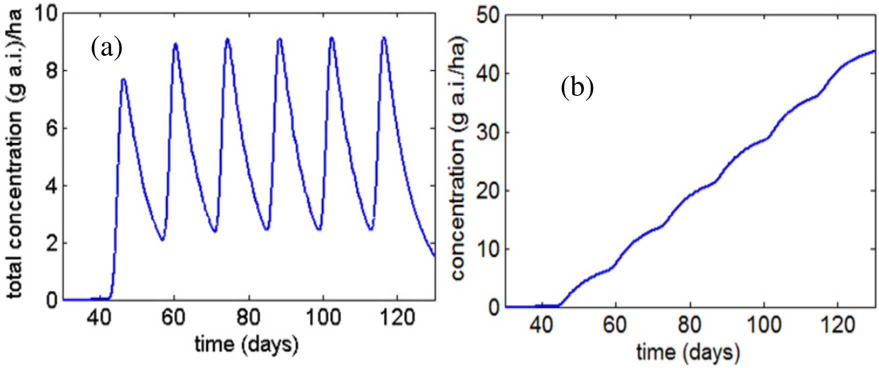

Figure 21: Six applications of Indoxacarb allocated as in table 5; (a) profile of the application scheme; (b) profile of accumulation rate in the environment

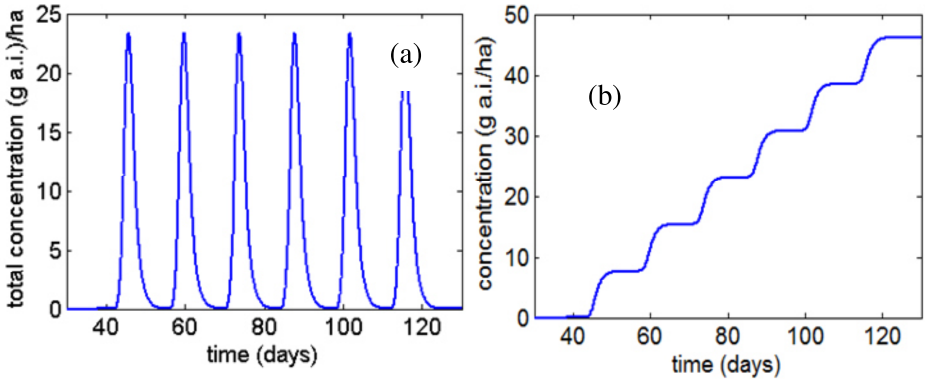

Figure 22: Six applications of Spinosad allocated as in table 6; (a) profile of the application scheme; (b) profile of accumulation rate in the environment

The six applications of the insecticides Indoxacarb and Spinosad are shown in figures 21a and 22a respectively. The effect of the DT_{50} is clearly observed. As expected, the insecticide Indoxacarb decays slowly compared to the insecticide Spinosad. A comparison between figure 21b and 22b shows that the rate of accumulation of Indoxacarb is slower than the rate of accumulation of Spinosad. This last result suggests that fast disappearing pesticides may also be fast accumulating pesticides in the environment.

3.7.3.1. With time continuous pest population model

– ***Application of Indoxacarb insecticide***

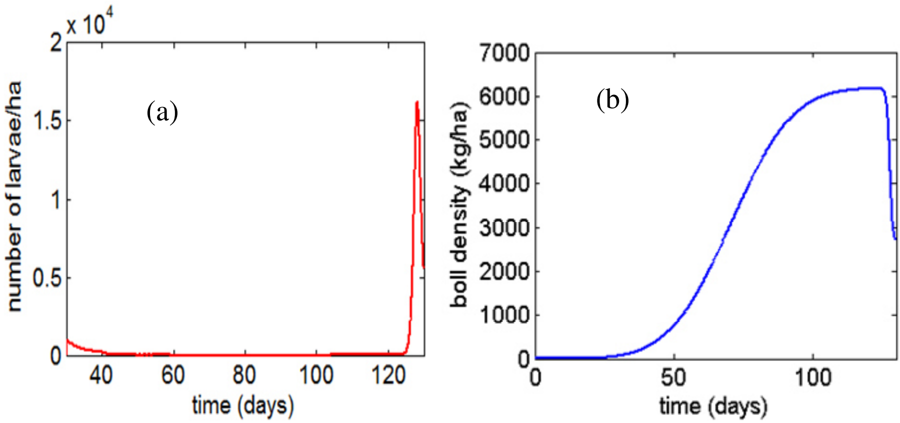

Figure 23: (a) Pest response to Indoxacarb following table 5; (b) crop response to pest after application of Indoxacarb following table 5

According to the results in figure 23, Indoxacarb could well control the pest until a certain time. It could be that the control would be totally effective if the application timing was distributed otherwise. Nevertheless, pesticides action on pest is clearly observed in figure 23a as pest is maintained at a low density until the end of insecticide applications. The crop development respond accordingly (figure 23b). When the pest density is low and cannot cause significant damage, the crop develops with no major pressure and when the pest is not controlled, an increase of pest density and a decrease of crop density are observed.

– ***Application of Spinosad insecticide***

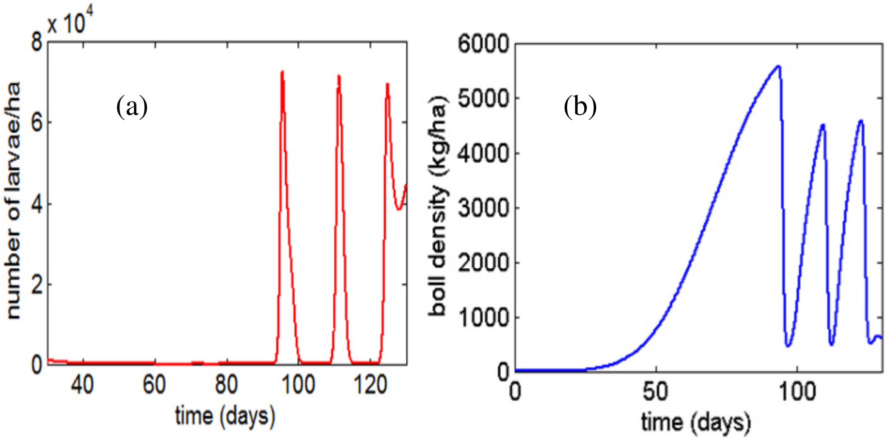

Figure 24: (a) Pest response to Spinosad following table 6; (b) crop response to pest after application of Spinosad following table 6

Figure 24 show that Spinosad could not control the pest with the considered application scheme. The first reason one can think of is the quick disappearance of the insecticide immediately applied (DT_{50}<1 day). Since crop dynamics is coupled to pest dynamics and vice versa, it could be that in the beginning of crop development, the crop density is low and therefore, the pest density in low and capable to be control by Spinosad. But latter, with high crop density, high infestation may occur and due to the quick disappearance of Spinosad, the pest is controlled just for a short time. This may explain the latter fluctuation in pest population density (figure 24a) and the crop dynamics response accordingly (figure 24b) due to its capacity to recover its losses (Nibouche et al. 2002).

3.7.3.2. With time discrete pest population model

– ***Application of Indoxacarb insecticide***

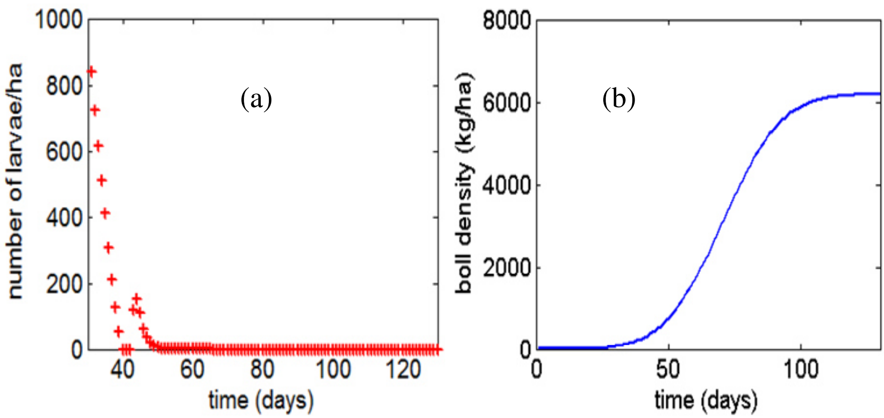

Figure 25: (a) Pest response to Indoxacarb following table 5; (b) crop response to pest after application of Indoxacarb following table 5

Indoxacarb could effectively control the pest with simulation made with time discrete pest population model (figure 25a) and crop dynamic responses accordingly (figure 25b).

– ***Application of Spinosad insecticide***

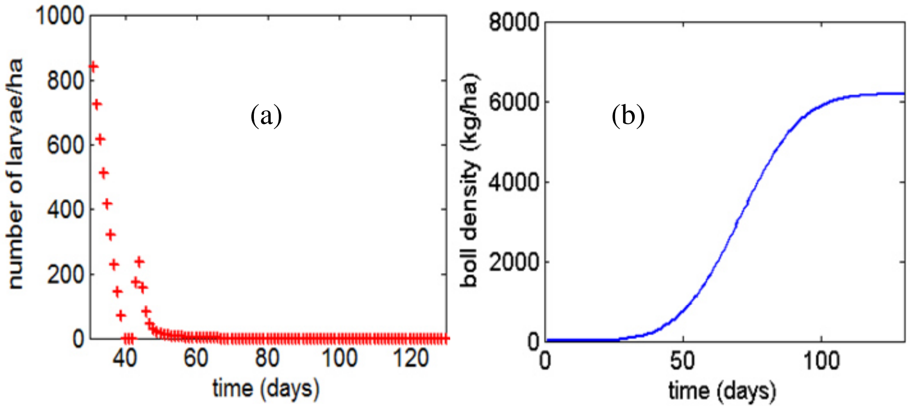

Figure 26: (a) Pest response to Spinosad following table 6; (b) crop response to pest after application of Spinosad following table 6

Spinosad could effectively control the pest with simulation made with time discrete pest population model (figure 26a) and crop dynamic responses accordingly (figure 26b).

A comparison of the time continuous pest population model with the time discrete pest population model shows that either the time continuous model overestimates the pest population dynamics or the time discrete model underestimates the pest population dynamics. Another point is that the time continuous model seems to be more sensitive to insecticide application than the time discrete model. Further development would be to couple crop dynamics to time discrete pest population dynamics, which we will not develop here. Nevertheless, with this model definition a thorough investigation of pesticide application strategies and their effects can be undertaken, which is the purpose of this thesis.

3.8. Pesticides transport in the soil

For a sound decision support system in agricultural pest management, it is very important to take into account environmental fate of pesticides, agricultural pesticides being potential sources of water pollution. To achieve this aspect of the DSS, a solute transport model is considered to evaluate the potential contamination of ground water by pesticides.

It is usually assumed that pesticides movement is a result of three processes (Wagenet and Rao 1990):

(i) Pesticide diffusion in the aqueous phase along a solute-concentration gradient;
(ii) Diffusion in the gas phase in response to a gradient in gas-phase concentration, if the pesticide is volatile;
(iii) Convection (mass flow) of the pesticide because of movement of the bulk fluid phase (water or gas) in which the pesticide is dissolved.

For water movement, in the case of precipitation or irrigation event, the basic equation is the mass conservation equation (26)

$$\frac{\partial \theta}{\partial t} = -\nabla \cdot \vec{q} + S_w \qquad (26)$$

With the relations

$$\vec{q} = -K(\theta)\nabla \psi \qquad (27)$$

and

$$\frac{\partial \theta}{\partial t} = \frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t} = C(\psi)\frac{\partial \psi}{\partial t} \tag{28}$$

one can derive the partial differential equation (29) for the matric potential ψ. More details regarding this derivation can be found in (Bear and Buchlin, 1991). The function $C(\psi)$ is referred to as the capacity function.

$$C(\psi)\frac{\partial \psi}{\partial t} = \nabla \cdot \left(K\nabla(\psi - z)\right) + S_w \tag{29}$$

The conductivity function K is written in the form $K = K_s K_r$, where K_s denotes the saturated conductivity, which is a parameter, and K_r is referred to as the normalized hydraulic conductivity parameterized as a function of the matric potential (30).

$$K_r = \frac{\left(1 - (\alpha|\psi|)^{n-1}\left(1 + (\alpha|\psi|)^n\right)^{-m}\right)^2}{\left(1 + (\alpha|\psi|)^n\right)^{m/2}} \tag{30}$$

The functional relationship between the water content θ and the soil matrix potential ψ is referred to as water retention curve. The shape of water retention curves can be characterized by several models. The most used is the van Genuchten (1980) parameterization (31).

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha|\psi|)^n\right)^{1-1/n}} \tag{31}$$

If pesticides degradation, sorption and desorption to the soil matrix obey linear kinetics, the adequate mass balance equations in the case of one site kinetic are:

$$\frac{\partial}{\partial t}(\theta c) = -\alpha_s (K_d c - s) - \theta k_l c \tag{32}$$

$$\frac{\partial s}{\partial t} = \alpha_s (K_d c - s) - k_s s \tag{33}$$

The general process-based model that describes pesticide fate in the unsaturated zone termed Convection-Dispersion-Equation (CDE) (34) includes the effects of sorption, liquid-, and vapor-phase transport; degradation and plant uptake.

$$\frac{\partial}{\partial t}(\theta c + \rho s + \varepsilon g) = \nabla \cdot \left[\theta D_h \nabla c + D_g \nabla g - \vec{q} c\right] + Q \tag{34}$$

In equation (34), D_h denotes the hydrodynamic dispersion coefficient (or tensor) that incorporates the effect of mechanical (i.e., flow-induced) dispersion and molecular diffusion upon pesticide movement in the liquid phase. The term Q summarizes all sources and sinks of the substance, i.e. all processes creating and consuming the substance.

With the assumption of a nonvolatile substance, the gaseous phase concentration is negligible. The kinetic equation (32) coupled with the transport equation (34) and the introduction of (28) into (34) yield (35)

$$\frac{\partial c}{\partial t}\theta + C(\psi)\frac{\partial \psi}{\partial t}c = \nabla \cdot [\theta D_h \nabla c - \vec{q}c] + Q - \alpha(K_d c - s) - \theta k_l c \qquad (35)$$

To solve this solute transport problem, boundary conditions must be specified. There are three possible ways:

- Dirichlet boundary condition (first type) specifies the values that a solution needs to take on along the boundary of the domain
- Neumann boundary condition (second type) specifies the values that the derivative of a solution is to take on the boundary of the domain
- Cauchy boundary condition (third type) is a specification of a linear combination of the values of a function and the values of its derivative on the boundary of the domain.

3.8.1. Application with Indoxacarb and Spinosad

Table 7 shows values for Soil hydraulic parameters for the van Genuchten model for 11 USDA soil classes. The sandy clay soil parameters are used in this example.

Table 7: Soil hydraulic parameters for the van Genuchten model for 11 USDA soil classes

	$\boldsymbol{\theta_s}$	$\boldsymbol{\theta_r}$	$\boldsymbol{K_s}$ **(m s^{-1})**	$\boldsymbol{\alpha}$**(m)**	$\boldsymbol{m}$
Sand	0.43	0.045	8.25e-5	14.5	0.627
Loamy sand	0.43	0.057	4.05e-5	12.4	0.561
Sandy loam	0.41	0.065	1.23e-5	7.5	0.471
Silty loam	0.45	0.067	1.25e-6	2.0	0.291
Loam	0.43	0.078	2.89e-6	3.6	0.359
Sandy clay loam	0.39	0.1	3.63e-6	5.9	0.324
Silty clay loam	0.43	0.089	1.97e-7	1.0	0.187
Clay loam	0.41	0.095	7.18e-7	1.9	0.237
Sandy clay	0.38	0.1	3.37e-7	2.7	0.187
Silty clay	0.36	0.07	5.78e-8	0.5	0.083
Clay	0.38	0.068	5.56e-7	0.8	0.083

(Shao and Irannejad 1999)

The hydrodynamic dispersion for solute transport considered here is a symmetric three dimensional tensor (36).

$$D_h = \begin{pmatrix} (D_{xx} + D_w) & D_{xy} & D_{xz} \\ D_{xy} & (D_{yy} + D_w) & D_{yz} \\ D_{xz} & D_{yz} & (D_{zz} + D_w) \end{pmatrix} \tag{36}$$

Where

$$D_{xx} = \frac{\alpha_T \left(v_y^2 + v_z^2\right) + \alpha_L v_x^2}{|\vec{v}|} \tag{37}$$

$$D_{yy} = \frac{\alpha_T \left(v_x^2 + v_z^2\right) + \alpha_L v_y^2}{|\vec{v}|} \tag{38}$$

$$D_{zz} = \frac{\alpha_T\left(v_x^2 + v_y^2\right) + \alpha_L v_z^2}{|\vec{v}|} \tag{39}$$

$$D_{xy} = D_{yx} = \frac{(\alpha_L - \alpha_T)v_x v_y}{|\vec{v}|} \tag{40}$$

$$D_{xz} = D_{zx} = \frac{(\alpha_L - \alpha_T)v_x v_z}{|\vec{v}|} \tag{41}$$

$$D_{yz} = D_{zy} = \frac{(\alpha_L - \alpha_T)v_y v_z}{|\vec{v}|} \tag{42}$$

v_i ($i=x,y,z$) is the component of the vector $\vec{v} = \vec{q}/\theta$.

The K_d value is related to the fraction of organic carbon in the soil f_{oc} and the sorption coefficient k_{oc} by $K_d = k_{oc} f_{oc}$
The soil organic content is less than 1% in some cotton plots in Burkina Faso according to the report of Traoré et al. (2007). This value is taken for f_{oc}. We assumed that pesticides only decays in the liquid phase therefore k_s=0.

Table 8: Physical properties parameter set for Indoxacarb and Spinosad

Property	Indoxacarb	Spinosad
k_l	0.035 *	0.69 *
k_{oc}	6450**	>2800***
K_d	64.5 *	28 *

*calculated values; **PPDB database; *** López and Fernández-Bolaños (2011)

Simulation is made for one application of the pesticide with the consideration of a homogeneous soil column of l=6m depth and no source or sink term. With c_0=10 g a.i./ha for Indoxacarb, c_0=60 g a.i./ha for Spinosad, q_0=0.002m/day may simulate a rain fall event, D_w=0.02 and α_s=0.0081/day and ψ_0=-1.5MPa. The values α_L=0.43m and α_T=0.043m are values for a homogeneous sandy aquifer reported in Freyberg (1988).

The upper boundary condition is given by specifying the water and solute fluxes at the surface of the soil column into the domain in the vertical direction such that

$$\begin{aligned} -\vec{n}\cdot\left(K\nabla\psi\right) &= q_0 \\ -\vec{n}\cdot\left(\theta D_h\nabla c - qc\right) &= q_0 * c_0 \end{aligned} \qquad (43)$$

Where $\vec{n}$ is the normal vector in the vertical direction, q_0 is the precipitation level and c_0 the input insecticide dose.

In the same way, the lower boundary condition is given by specifying the water and solute fluxes at the lower boundary of the soil column out of the domain in the vertical direction such that

$$\begin{aligned} \vec{n}\cdot\left(K\nabla\psi\right) &= K \\ \vec{n}\cdot\left(\theta D_h\nabla c - qc\right) &= K * c \end{aligned} \qquad (44)$$

- Simulation for the transport of Indoxacarb

Figure 27 shows that the soil matric potential is less negative, expressing a slow movement of water into the soil. Figures 28 and 29 can be summarized by figure 30. The liquid phase concentration and the solid phase concentration at 1.5m below the soil surface (figure 30a and b) remain constant after a while due to the retention capability of the soil, which is in good agreement with figure 27, and the relatively strong binding of Indoxacarb. The peak on the solid phase concentration curve (figure 30b) can explain the breakthrough of the chemical when travelling into the soil.

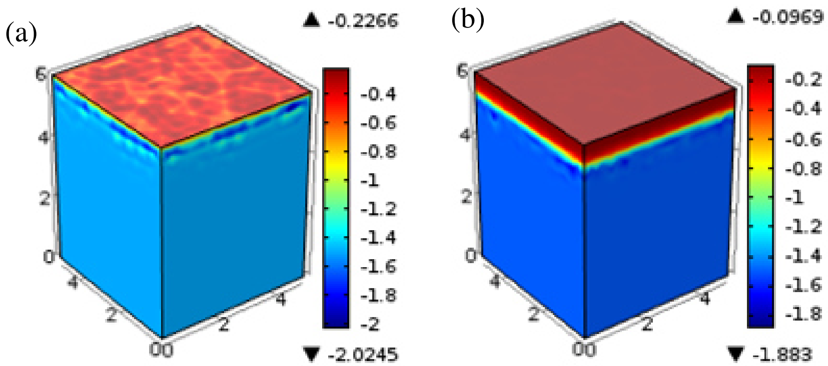

Figure 27: Soil matric potential at the beginning of the simulation (a) and 20 days later (b)

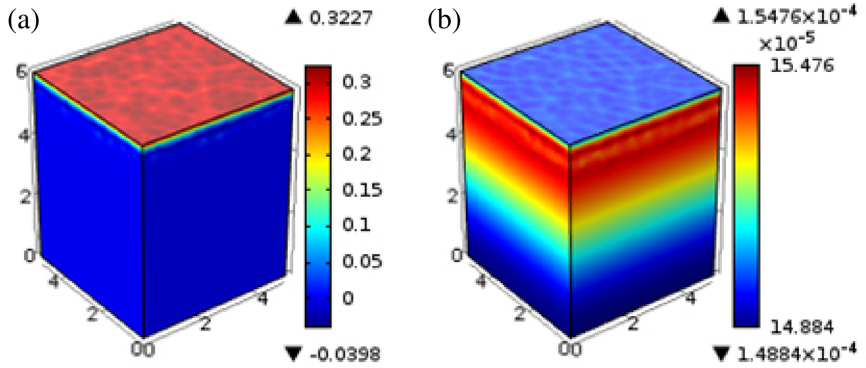

Figure 28: Liquid phase concentration of Indoxacarb transport in the soil; (a) at the beginning of the simulation and (b) 20 days later

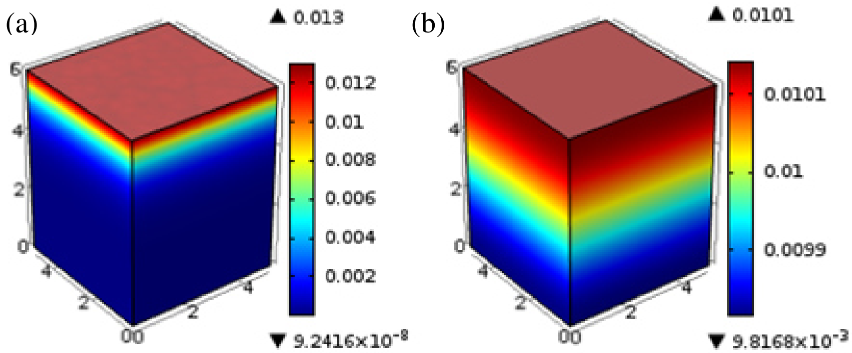

Figure 29: Solid phase concentration of Indoxacarb transport in the soil; (a) at the beginning of the simulation and (b) 20 days later

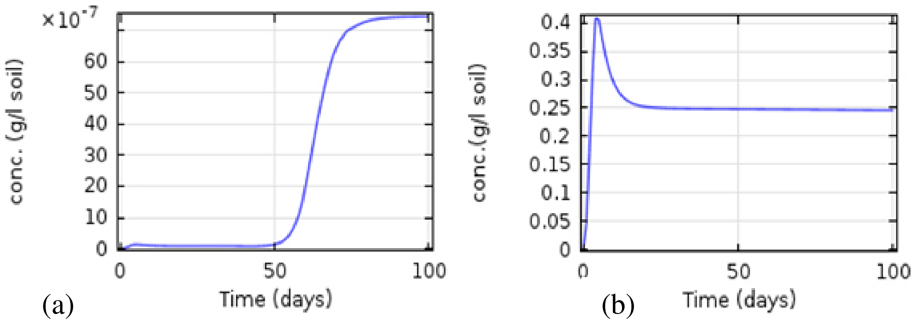

Figure 30: (a) Liquid phase concentration and (b) solid phase concentration dynamics of Indoxacarb at l=1.5m below the soil surface

❖ Simulation for the transport of Spinosad

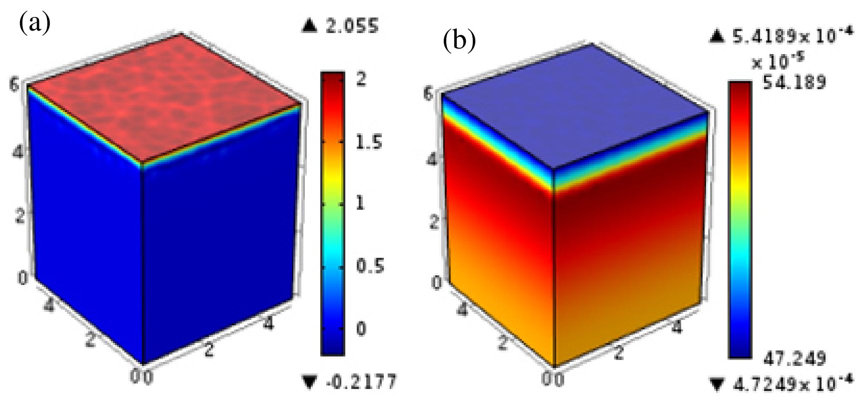

Figure 31: Liquid phase concentration of Spinosad transport in the soil; (a) at the beginning of the simulation and (b) 20 days later

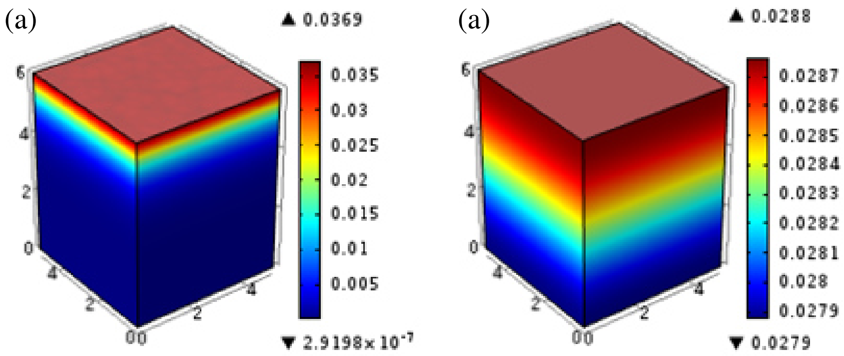

Figure 32: Solid phase concentration of Spinosad transport in the soil; (a) at the beginning of the simulation and (b) 20 days later

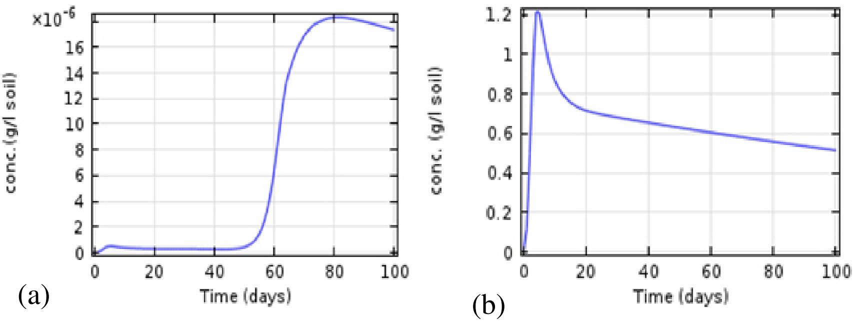

Figure 33: (a) Liquid phase concentration and (b) solid phase concentration dynamics of Spinosad at l=1.5m below the soil surface

Figures 31 and 32 can be summarized by figure 33. In figure 33a, the liquid phase concentration of Spinosad at 1.5m below the soil surface increases gradually until its maximum and decreases slowly; this is due to the solute capability of retention in the soil medium, which is in good agreement with figure 27. The peak on the solid phase concentration curve (figure 33b) can explain the breakthrough of the chemical when travelling into the soil. The gradual decrease points out the relatively weak binding of Spinosad to the soil medium.

3.9. Regionalization

3.9.1. Cotton plant

The factors determining the suitable application of the cotton growth model developed in this study are i) the cotton species. Cotton yield strongly depends on the cultivated species. In Burkina Faso and Australia for example, the most grown species is *Gossypium hirsutum* known as the most productive (The cotton industry development and delivery team 2011). ii) the cultural practice, here the spread of plants within the farm. According to Australian cotton growers, to optimize yield, one should aim for an evenly spaced plant population from 5-13 plants per meter. In this way, yield may differ from one farm to another under the same soil and weather conditions. iii) Yield can also differ between regions due to rain fed or irrigated crops, and the variability between and within seasons. iv) The optimal sowing window. Failing to obtain a sowing opportunity can substantially influence crop yield.

3.9.2. *Helicoverpa armigera* population dynamics

Temperature has a great effect on the survival, development, fecundity and longevity of *Helicoverpa armigera.* Thereby, the completion of the life cycle of the pest differs between regions.

The neighborhood vegetation plays a great role in the sustainment of the population density in a plot. This vegetation can act as refuge when there is no crop. It can also be source of pest outbreaks to the cropping area through adults' migration. The neighborhood vegetation can also be cropping areas; in this case, adults will migrate from plots to plots causing fluctuations of pests over time and space. The two most important factors influencing flight behavior and the displacement of *Helicoverpa* moths are wind speed and wind direction; the minimum wind speed that influences flight orientation is 1 $m.s^{-1}$, below this threshold moths may fly in any direction, but they still tend to maintain fixed trajectories (Riley et al., 1992). *Helicoverpa* fly predominantly at night, taking off at dusk (Dillon et al., 1996).

Adult dispersal can be incorporated into the DSS via the model below, with the assumption of short distance migration within a cropping area with less than 1 $m.s^{-1}$ wind speed. The time continuous coupled spatial and population dynamics processes are described by a system of reaction diffusion equations of the following general form:

$$\frac{\partial N_i}{\partial t} = L_o[N_i] + f_i(N_1, N_2, \cdots, N_n) \qquad i = 1, \cdots, n \tag{45}$$

Where L_o denotes the differential operator for spatial processes. Here, L_o is the classical diffusion operator $\nabla \cdot D\nabla$ in its simple form. The reaction terms $f_i(N_1, N_2, \cdots, N_n)$ model population dynamics and genetics and the interactions between different species or biotypes of the same species. The partial differential equations describing the dynamics of the pest in its adult and larval life stages (46 and 47 respectively) are as follow.

$$\frac{\partial A}{\partial t} = \nabla \cdot (D_A \nabla A) + r\gamma_H H - \mu_A A + S_p \tag{46}$$

The boundary condition can be specified as in paragraph 3.8 and the initial condition is set such that $A(t=0)=A_0 \geq 0$

With the consideration that larvae do not move, the differential operator for spatial processes is not applied for larvae

$$\frac{\partial H}{\partial t} = \varphi_H \left(1 - \frac{H}{K_{ap}}\right) A - (\gamma_H + \mu_H) H \tag{47}$$

With the initial condition $H(t=0)=H_0 \geq 0$

The environmental capacity is made biomass dependent by relation (48), where *B* is the biomass density (cotton boll biomass).

$$K_{ap} = \alpha_B B + K_0 \tag{48}$$

3.9.2.1. Application of the pest dispersal model

For application, we constructed a domain divided into plots (subdomains) as shown in figure 34. The domain and subdomains are realized in the finite elements tool COMSOL Multiphysics environment. The non-linear initial boundary value problems form of equations 4, 6, 7, 46 and 47 are to be solved over geometries of the domain. It is assumed that there is no flow of adults (moths) at the borders of the domain; thereby $\vec{n} \cdot (-D_A \nabla A) = 0$ at the boundary, where $\vec{n}$ is the outward normal vector.

It is possible to have different parameters or even different PDEs in each subdomain, but this situation is beyond the scope of our study.

The proportion A_0 of initial moths in the whole field is based on an assumed normal distribution. It is the superposition of the proportion of moths $A_{0(x_i,y_i)}$ allocated at points of space coordinates $(x_i, y_i)_{i=1,\cdots,n_H}$ into each plot. A_0 is written as follow

$$A_0 = \sum_{i=1}^{n_H} A_{0(x_i,y_i)} e^{\left(-\frac{(x-x_i)^2}{2\sigma_x^2} - \frac{(y-y_i)^2}{2\sigma_y^2}\right)} \tag{49}$$

The pupal survivorship in table 2 is considered for the emergence rate μ_A, and the female to male ratio is considered to be 1:1.
In figure 34, the spots are the initial sources from which the pest will disperse over the plots. It is assumed that the first pests are found 31 days after crop planting.

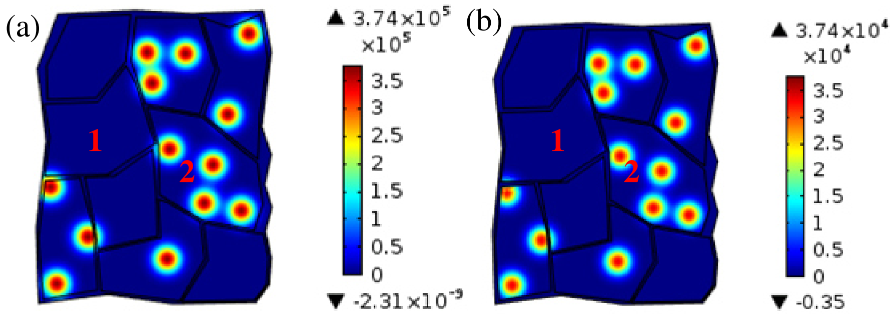

Figure 34: Initial pest distribution in the domain. (a) adults distribution; (b) larvae distribution

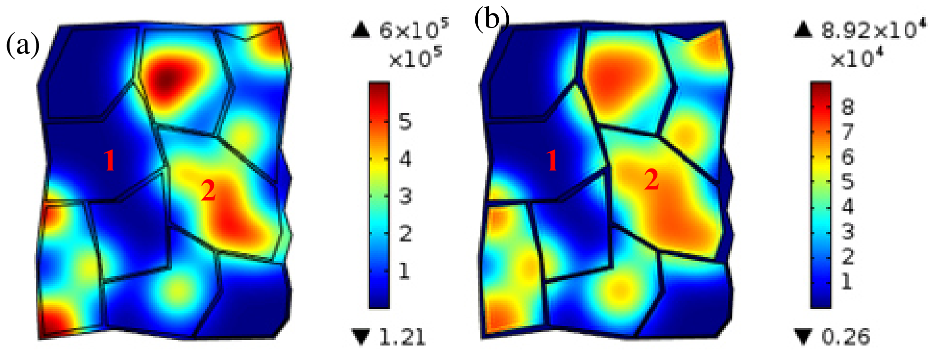

Figure 35: Pest dispersal in the domain 50 days later. (a) adults dispersal; (b) larvae dispersal

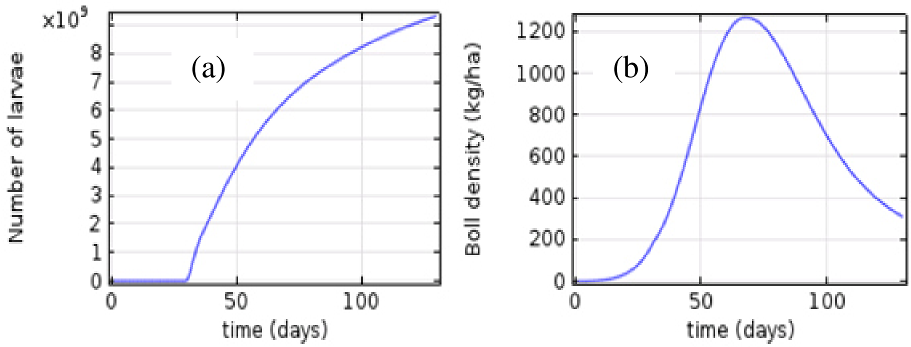

Figure 36: Pest and crop dynamics in plot 1. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population of figure 36a

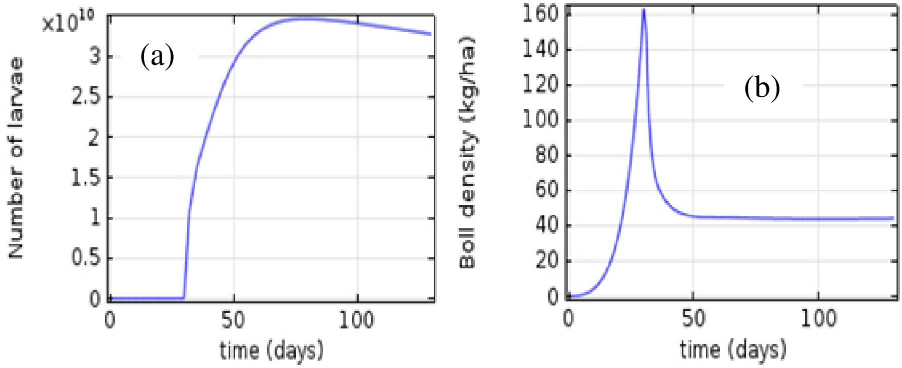

Figure 37: Pest and crop dynamics in plot 2. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population of figure 37a

A comparison between plot 1 and plot 2 exhibits the mobility behavior of the pest. In the beginning of pest invasion, plot 1 is not infested (figure 34) and the crop is growing with no stress from the pest. After a while plot 1 is progressively invaded (figure 35) by the neighboring pest population. This progressive invasion in plot 1 can explain the smooth decrease of its biomass (figure 36b). On the other hand plot 2 has a rapid decrease of biomass (figure 37b) due to a high initial invasion of the pest.

In this simulation, we considered small scale migration of moths with small values of the coefficient of dispersion. It is also possible and should account for future investigations to take into account large scale migration because *H.A.* has a high mobility status. According to Dillon et al. (1996), *Helicoverpa* moths fly at an average unassisted flight speed of 4 m per second (14.4 km.h^{-1}), for up to 5 h duration. Based on the concept of oogenesis-flight syndrome, Johnson (1969) assumed that the long-distance migration duration is about 2 to 3 nights, from the second night of emergence to oviposition.

Attractiveness also plays a great role in the migration of moths. Feng et al. (2010) reported that the relative attractiveness to *Helicoverpa Armigera* moths varies with the type and the stage of crops and flowering host are generally more attractive. This aspect can be included into the DSS via chemotaxis consideration.

3.9.3. Insecticides application

Insecticide application scheme may differ from one farmer to another. Insecticides application coupled to larvae dynamics yield equation 50.

$$\frac{\partial H}{\partial t} = \varphi_H \left(1 - \frac{H}{K_{ap}} \right) A - (\gamma_H + \mu_H) H - \mu_p R_{cont}(P(t))H \tag{50}$$

The dynamic system (equations 4, 6, 7, 21, 22, 46 and 50) is solved by finite elements method over the geometry of figure 34 with application of the insecticide Indoxacarb for pest control. Results are presented in the following scenarios as an approach to management.

3.9.4. Some management scenarios

The following scenarios are considered:

- Scenario 1: The insecticide (Indoxacarb) is applied on all plots following the application scheme of table 5;

- Scenario 2: The insecticide (Indoxacarb) is applied on all other plots following the application scheme of table 5, except on plot 1 where no control measure is undertaken;
- Scenario 3: The insecticide (Indoxacarb) is applied on all plots following the application scheme of table 9. The recommended dose is increased to 50g a.i./ha;

Table 9: An application scheme with Indoxacarb insecticide

Dose (g a.i./ha)	50	50	50	50	50	50
Time (days after planting)	45	59	73	87	101	115

- Scenario 4: The insecticide (Indoxacab) is applied on all other plots following the application scheme of table 9, except on plot 1 where no control measure is undertaken.

Scenario 1. The insecticide (Indoxacarb) is applied on all plots following the application scheme of table 5

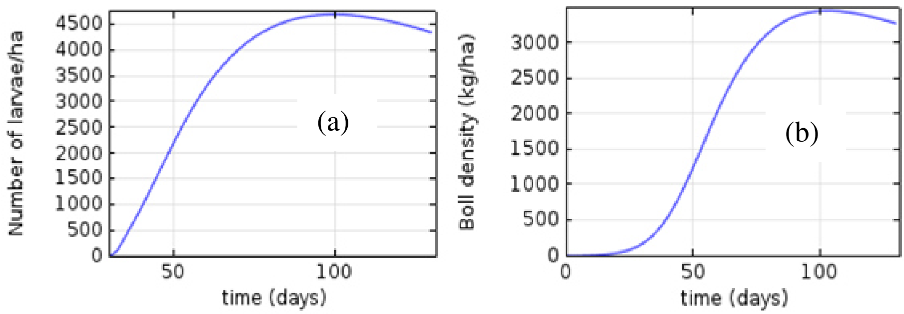

Figure 38: Pest and crop dynamics on plot 1. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population. Insecticide is applied according to table 5

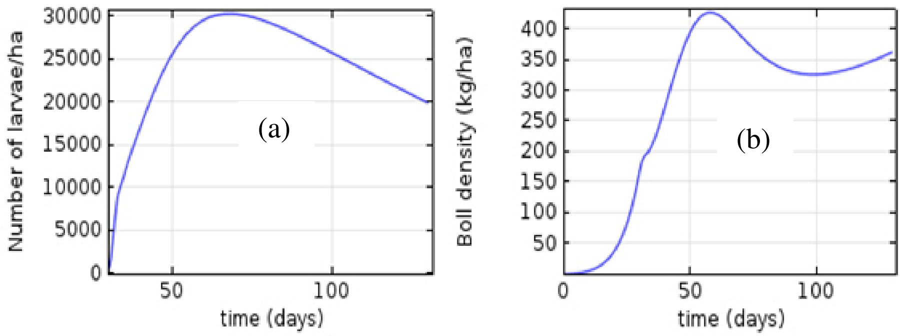

Figure 39: Pest and crop dynamics on plot 2. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population. Insecticide is applied according to table 5

In scenario 1, insecticide is applied according to the application scheme of table 5, that is 6 applications at a dose of 10g a.i./ha each. Due to adults' dispersal, plot 1 is also infested (figure 38a) and the effect on the crop is reduced (figure 38b) owing to insecticide application. It is observable on figure 39 that the application scheme considered did not effectively control the pest. Compared to the results of figures 23a and 23b, the control is less efficient. It seems that solving the differential equations with adults' dispersal induces the reduction of the effect of insecticides on the pest or, conversely, solving the ODEs without adults' dispersal increases the effect of insecticides on the pest. It should be taken into account when making decisions. Further investigations of this result are recommended with different separate data.

Scenario 2. The insecticide (Indoxacarb) is applied on all other plots following the application scheme of table 5, except on plot 1 where no control measure is undertaken

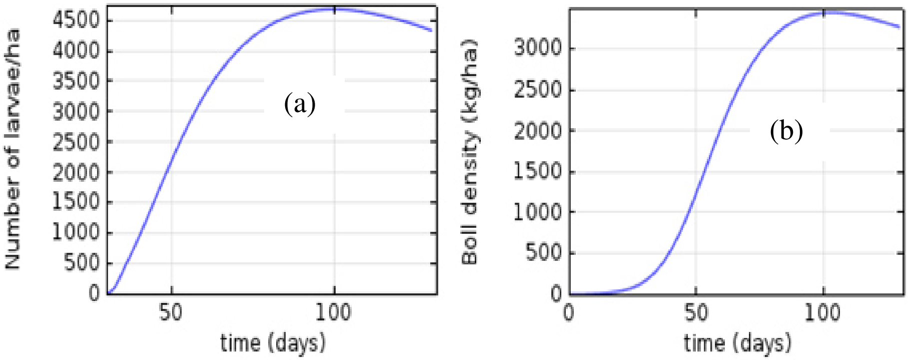

Figure 40: Pest and crop dynamics on plot 1 where no control measure was undertaken. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population

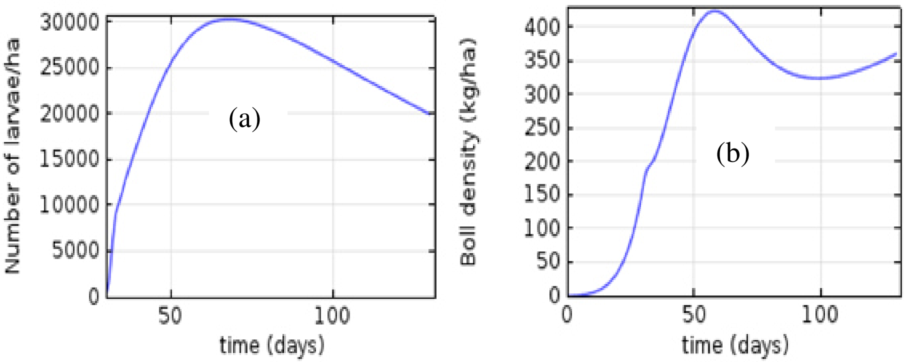

Figure 41: Pest and crop dynamics on plot 2 with insecticide application according to table 5. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population

Scenario 2 emphasizes on what is said in scenario 1. Results on plot 1 of scenario 1 figure 38 and results on plot 1 scenario 2 figure 40 are unexpectedly equal, although there have been no control measure on plot 1 scenario 2. This suggests that the application scheme considered was of no used for plot 1. Plot 2 scenario 2 received the same treatment as plot 2 scenario 1 and yielded the same expected results (figure 41).

In order to have a closer look into the unexpected effect, we increased dispersal and consumption terms with Indoxacarb application scheme in all plots. The results obtained are observed in figures 42, 43 and 44. Figure 42 presents the spread of adults in the field. Figure 43 shows the spread of larvae due to the dispersal of adults and figure 44 is the outcome of cotton boll dynamics in the presence of voracious larvae. The part colored in red on the figures indicates the presence of adults, larvae and cotton boll on respective figures. The fact that there was identical result in the two scenarios as stated above can be explained by the dispersal term. In plot 1 scenario 2 where no control measure was undertaken, the pest did not migrate enough to this plot to cause more damage as it is the case in figure 44. This limitation in migration was due to insecticides applied on all plots except on plot 1 (scenario 2).

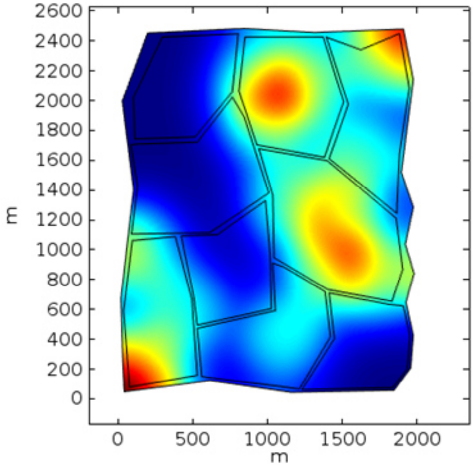

Figure 42: Adults dispersal with high dispersal coefficient

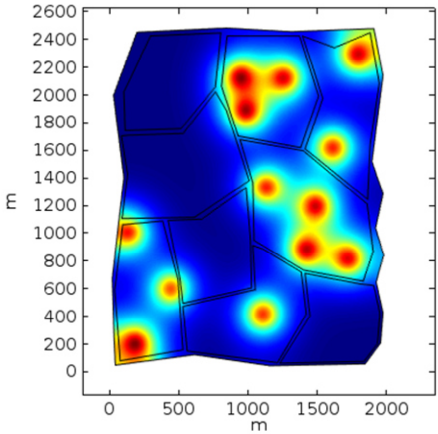

Figure 43: Larval dispersal with high adult dispersal coefficient

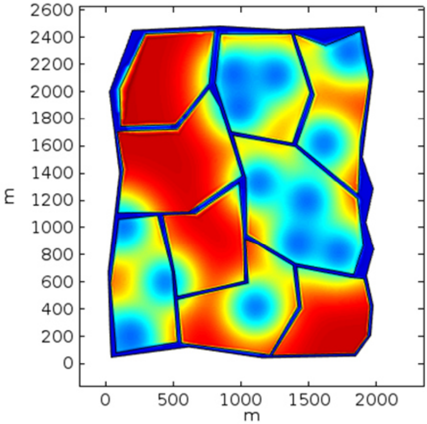

Figure 44: Boll dynamics with high consumption rate

Scenario 3. The insecticide (Indoxacarb) is applied on all plots following the application scheme of table 9

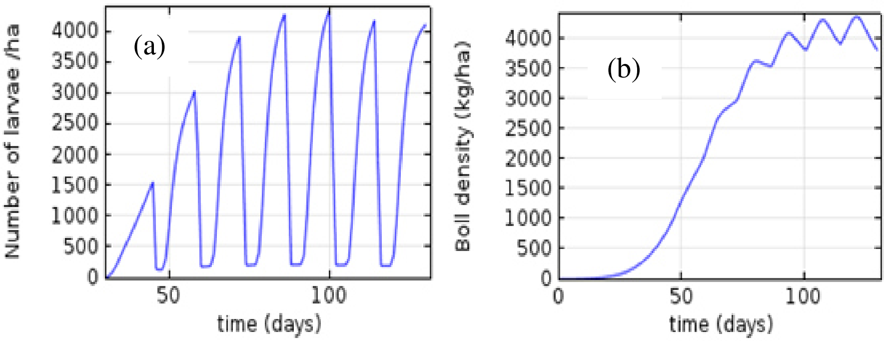

Figure 45: Pest and crop dynamics on plot 1. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population. Insecticide is applied according to table 9

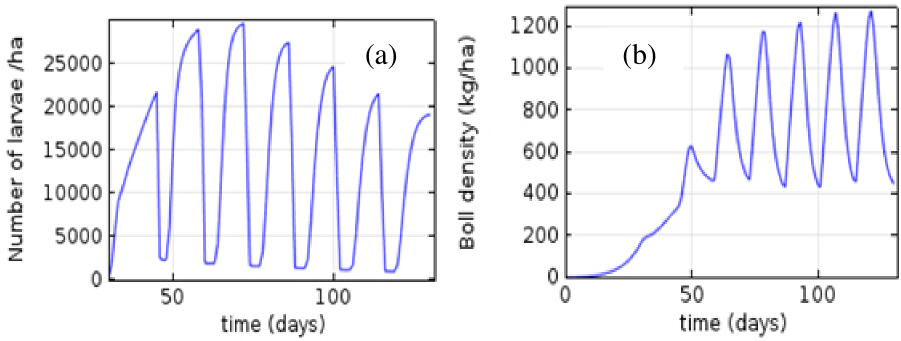

Figure 46: Pest and crop dynamics on plot 2. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population. Insecticide is applied according to table 9

In scenario 3, the same application scheme is considered but with an increased dosage 50ga.i./ha per treatment. The effect of the control measure is clearly observed on the pest dynamics (figures 45a and 46a) and the crop dynamics respond accordingly (figures 45a and 46b). This application scheme had a considerable effect on pest population density but yet not enough to maintain the pest population at a reasonable lower density that would bring better yield.

Scenario 4. The insecticide (Indoxacab) is applied on all other plots following the application scheme of table 9, except on plot 1 where no control measure is undertaken.

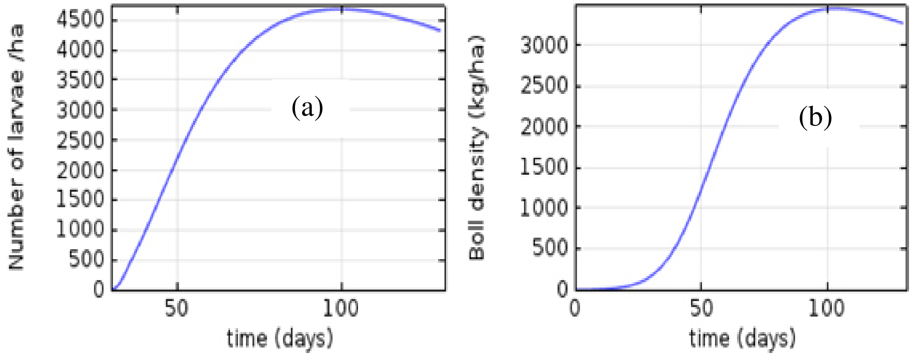

Figure 47: Pest and crop dynamics on plot 1 where no control measure was undertaken. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population. Insecticide is applied according to table 9

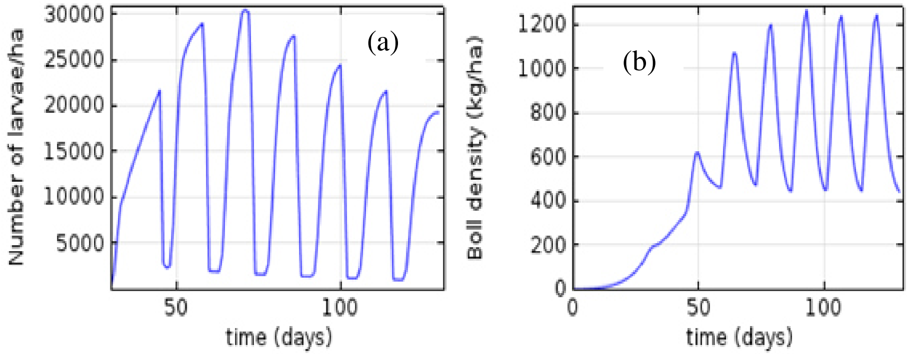

Figure 48: Pest and crop dynamics on plot 2. (a) population dynamics of larvae; (b) cotton boll dynamics response to pest population. Insecticide is applied according to table 9

In scenario 4, the dosage scheme of 50 g a.i./ha is applied on all plots except on plot 1. Plot 1 is gradually invaded by the pest resulting from the neighboring plots until insecticides application. The control measure provided induces the decrease of pest population density (figures 47a and 48a). But the decrease in pest population density on plot 1 is slower than on plot 2, suggesting that pest population may keep on growing on plot 1, when stressed on other plots. **Plot 1 in this case served as pest's refuge** and crop dynamic responded accordingly. But plot 1 is not as damaged as it could be (figure 47b) in the case of no pests control on the other plots.

From these scenarios, one can derive the following hypothesis:

- All farmers are concern by pests' management.
- The calendar based spraying program has a weakness as pest management strategy in agriculture in the sense that one may apply pesticides on his farm when there is no need (scenario 2).
- There is an application scheme that could substantially control the pest. This point will be investigated in the optimization part.

3.9.5. Insecticides resistance

Extended use of pesticides may result to the development and spread of resistant pest population. Dillon et al. (1996) points out that moth immigration and emigration directly affect the population distribution, density, demography and genetic composition within the regional landscape. Likewise for Qifa and Caprio (2002), extensive gene flow occurs at local and regional scale. In China, insecticide resistance monitoring and restriction fragment length polymorphism analysis of the genetics of populations collected from different geographical regions showed that there are frequent gene exchanges between populations in different ecological regions in China (Wu and Guo 2000, Xu et al. 2002). Therefore, **individual farmer's actions should not be isolated from those of others in the case of pesticides resistance management**. **Regional management should be considered**. This aspect of the DSS will be the subject of the pesticides resistance modeling part.

3.9.6. Solute transport

The model developed for solute transport is derived under the assumption of homogeneous soil. However, physical properties and chemical composition of real soils are inhomogeneous and may vary from one region to another. Precipitation plays a great role in the chemical infiltration in soil. **Most benefit comes from simulating growers' specific conditions using their own soil type and farming practices**.

3.10. Insecticides resistance modeling and application to H.A.

Brown (1996) defined evolution of resistance as a process in which the frequency of genes for resistance increases in a population of a pest so that an increased proportion of that population survives when the pesticide is applied at the originally efficacious dose. For Daly (1993), resistance is seen to be the product of the interactions between (1) selection pressure on the different genotypes in the presence and absence of the selecting agent (the insecticide), and (2) gene flow, usually within a Mendelian population. Brown (1996) reported that there are approximately 600 species resistant to insecticides. Many of these are species of practical impact and some are very troublesome due to having evolved to most of the pesticides registered for use against them. Development of resistant *Helicoverpa armigera* populations has been reported in many countries and has caused huge economic losses and even catastrophes to cotton production (Djihinto et al. 2009). The current costs for developing products and the loss of a product prematurely due to resistance development would be disastrous to a company (Thompson 1997). Resistance management is therefore a critical facet of pest management.

Observing resistance on a genotypic level is critical for the understanding of resistance evolution and for the accurate formulation of resistance management strategies Brown (1996). Insecticides resistance will be described in this study through relatively simple mathematical models. Two major aims of simple models in evolutionary genetics are to predict the speed of change through time of frequencies of different genes already present in a population (gene substitution), and to determine the possibility of establishment of a rare mutant in a genetically homogeneous resident population (invasion) (Nisbet et al. 1989).

Various mechanisms of resistance have been developed by *H.A.*, such as oxidative metabolism of insecticides, nerve insensitivity to pyrethroids, penetration resistance, and metabolism because of esterase (Ahmad et al. 1989; Gunning et al. 1991; Kranthi et al. 1997, 2001; Martin et al. 2002; Yang et al. 2008). Since the metabolic resistance is inherited as a single major gene, mixed-function oxidase (*mfo*), and annual fluctuations in resistance appear to be a result of changes in allele frequency at the *mfo* locus (Daly 1993), the simplest case of a single locus with two alleles denoted as *r* and *s* are considered. Resistance is assumed to be transferred by allele *r*. Since gene flow is considered at the field scale, a convenient general mathematical structure is a system of partial differential equations given by Richter and Seppelt (2004) that we will apply to the insect population dynamics (51, 52).

$$\frac{\partial H_i}{\partial t} = \underbrace{r_{H_i}\left(\vec{H}, \vec{A}\right)}_{(a)} - \underbrace{\mu_{H_i} H_i \left(1 + \sum_{j=1}^{n} \alpha_{i,j} H_j\right)}_{(b)}, \qquad i = 1, \cdots, u \tag{51}$$

$$\frac{\partial A_i}{\partial t} = \underbrace{r_{A_i}\left(\vec{H}, \vec{A}\right)}_{(a)} - \underbrace{\mu_{A_i} A_i \left(1 + \sum_{j=1}^{n} \alpha_{i,j} A_j\right)}_{(b)} + \underbrace{\nabla \cdot D_i \nabla A_i}_{(c)}, \qquad i = 1, \cdots, u \tag{52}$$

We considered the immobile (larvae) and the mobile (adults) life stages given by equations (51) and (52) respectively. The processes are formulated of pest dynamics and spatial dispersal, and exchange of genetic information: with u=3 populations of different biotypes with the population densities denoted by H_i for larvae density of biotype i and A_i for adults density of biotype i ($i=1,\ldots,u$). Population growth and the underlying genetic processes are incorporated by term (a). Term (b) models the species dependent mortality with a parameter μ_i and the interspecific competition coefficient $\alpha_{i,j}$. term (c) describes the spatial spread of species by a simple diffusion-type process.

The functions $r_{H_i}\left(\vec{H}, \vec{A}\right)$ are derived from the Hardy-Weinberg theory (Nisbet et al., 1989): In our case where a diploid species with resistant and sensitive alleles is considered, the genotypes are then homozygote resistant (*rr*), heterozygote (*rs*) and homozygote sensitive (*ss*) (i.e. u=3) where the indices *r* stands for resistant and *s* for sensitive.

The submodel (53) describes the mating of the diploid species. r_i is the maximal oviposition rate of biotype A_i and E_i is the number of eggs of genotype $_i$. $A = A_{rr} + A_{rs} + A_{ss}$

$$r_{H_{rr}}\left(\vec{H},\vec{A}\right)= r_{rr}\frac{1}{A}\left(A_{rr}+\frac{1}{2}A_{rs}\right)\left(E_{rr}H_{rr}+\frac{1}{2}E_{rs}H_{rs}\right)$$

$$r_{H_{rs}}\left(\vec{H},\vec{A}\right)= r_{rs}\frac{1}{A}\left[\left(A_{ss}+\frac{1}{2}A_{rs}\right)\left(E_{rr}H_{rr}+\frac{1}{2}E_{rs}H_{rs}\right)+\left(A_{rr}+\frac{1}{2}A_{rs}\right)E_{ss}H_{ss}\right]$$

$$r_{H_{ss}}\left(\vec{H},\vec{A}\right)= r_{ss}\frac{1}{A}\left(A_{ss}+\frac{1}{2}A_{rs}\right)\left(E_{ss}H_{ss}+\frac{1}{2}E_{rs}H_{rs}\right)$$

$$(53)$$

It is assumed that adults' dynamics is proportional to the larval density. r is the proportion of female adults and γ_{H_i} is the emergence rate for genotype i.

$$r_{A_i}\left(\vec{H},\vec{A}\right)= r\gamma_{H_i}H_i \qquad (54)$$

In the case of no competition, $\alpha_{i,j}=0$. The resulting system of partial differential equations to be solved is coupled with a capacity function.

$$\frac{\partial H_i}{\partial t}= r_{H_i}\left(\vec{H},\vec{A}\right)\left(1-\frac{H_i}{K_{ap}}\right)-\left(\mu_{H_i}+\gamma_{H_i}\right)H_i \qquad i = rr, rs, ss \qquad (55)$$

$$\frac{\partial A_i}{\partial t} = r\gamma_{H_i} H_i - \mu_{A_i} A_i + \nabla \cdot (D_i \nabla A_i) \qquad i = rr, rs, ss \qquad (56)$$

With the initial condition $H_i(t=0) = H_{i0} \geq 0$ and $A_i(t=0) = A_{i0} \geq 0$. The parameters with the property of resistance are the mortality rates μ_{p_i}. The parameters μ_{p_i} depend on the pesticide concentration in the plot, and hence on the degree of resistance of the considered biotype.

3.10.1. Application of the resistance model to *helicoverpa armigera*

We solved the dynamic system form of equations (55) and (56) with omission of the dispersal term and with a constant K_{ap}=10000/ha which is the amount of larvae that can cause irremediable crop damage (Nibouche et al. 2002). We assumed that there exists a very low density of homozygous resistant and heterozygous populations in the initial pest population density. Figure 49 illustrates the development of pesticides resistance in insects with initially existing low density resistant individuals. Every time chemicals are sprayed a few naturally resistant individuals of the targeted population survive and create a new generation of pests that are poison-resistant. That generation breeds another more-resistant generation.

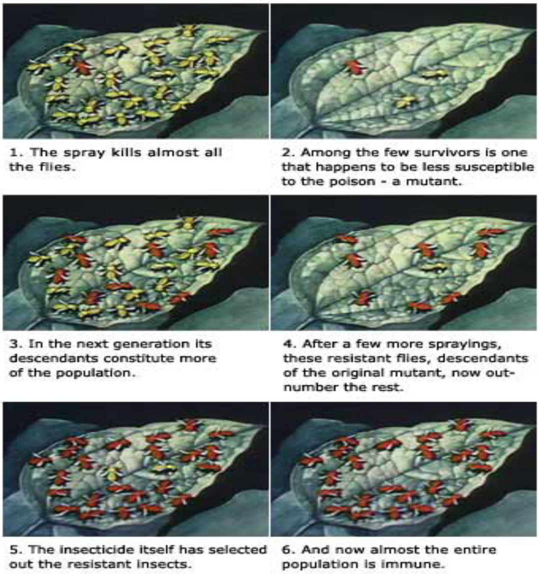

Figure 49: Diagram showing development of pesticides resistance in insect
(Evolution library 2001)

We considered the initial population distributed as follow:

$H_{0_{rr}} = H_{0_{rs}} = A_{0_{rr}} = A_{0_{rs}} = 0.001 / ha$ and $H_{0_{ss}} = 10 \quad A_{0_{ss}} = 1000 / ha$

And the following value for oviposition parameters:

$E_{rr} = 0.00025; \quad E_{rs} = 0.00025; \quad E_{ss} = 26; \quad r_{rr} = r_{rs} = r_{ss} = 26 / day$

Results in figures 50 and 51 are obtained in the case of no insecticide application.

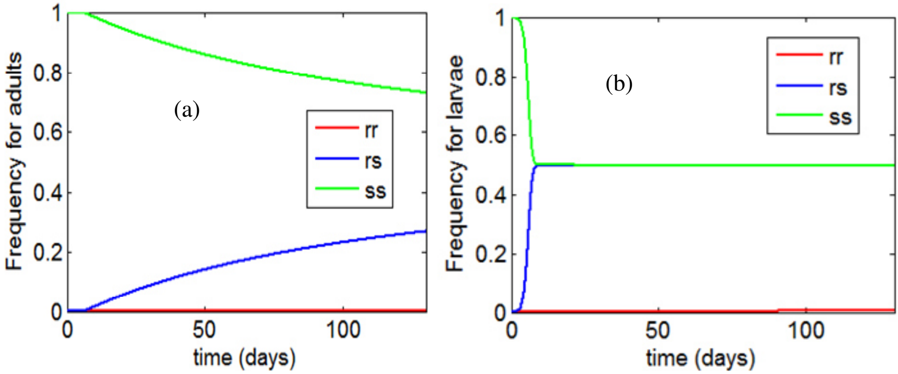

Figure 50: Evolution of frequencies of the genotypes in the population with no insecticide application (a) for adults and (b) for larvae

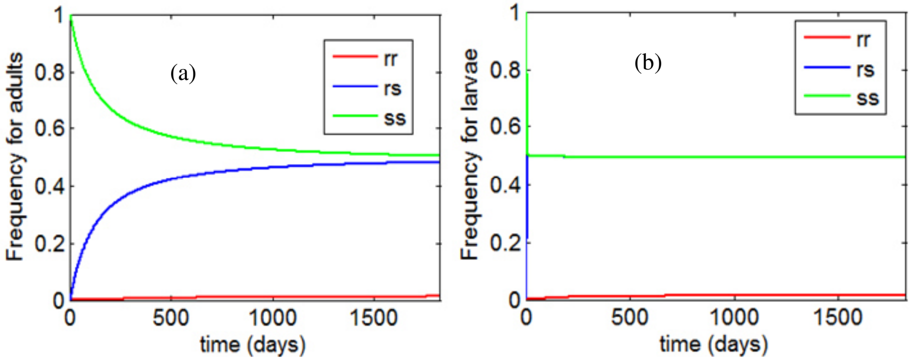

Figure 51: Evolution in 5 years of frequencies of the genotypes in the population with no insecticide application (a) for adults and (b) for larvae

With the specified initial conditions, the frequencies of genotypes *rs* and *ss* tend to stabilize at equal frequencies for adults (figure 50a) and for larvae (figure 50b) during the considered growing period of 130 days. Within a period of 5 years in our case, the larvae *rs* and *ss* are stable in equal frequencies (figure 51b) and the genotype frequency *rr* is also showing up (figure 51a). This result has been reported by McKenzie and Clarke (1988) and Raymond et al. (1993). They stated that in the absence of insecticide treatments, insecticide resistance may be stable or unstable. The most likely cause of instability of insecticide resistance in the absence of insecticide treatments is a fitness cost associated with resistance.

In the case of insecticides application, the following parameter values were used:

$\mu_{p_{rr}} = 0/day \quad \mu_{p_{rs}} = 1/day \quad \mu_{p_{ss}} = 10/day \quad th_{r_{rs}} = 10 \quad th_{r_{ss}} = 5$ the other parameters values are those of Indoxacarb.

A cohort of individuals followed in a period of 5 years with insecticide application yielded results in figures 52 and 53. Figure 52a presents the insecticide application scheme and figure 52b the concentration of insecticide that accumulates in the environment. In figure 53, the resistant genotype has slightly increased in frequency compared to figure 51, shown by the blue dashes in figure 53b for the heterozygous population. This indicates that insecticides hasten the evolution of resistant pests. This result was discussed by many authors among which Nisbet et al. (1989).

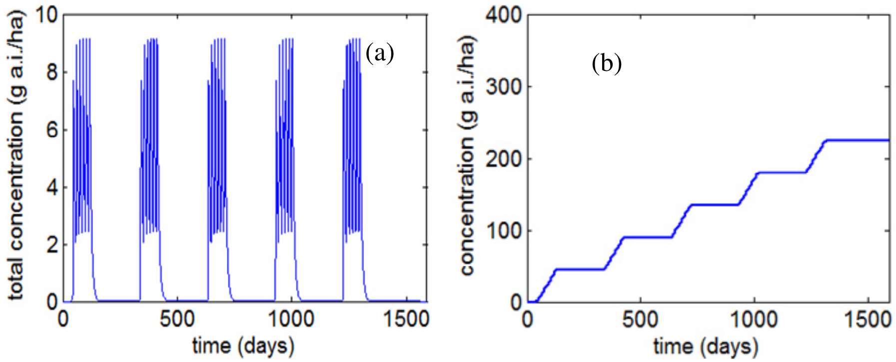

Figure 52: 5 years insecticide application scheme (a) and accumulation in the environment (b)

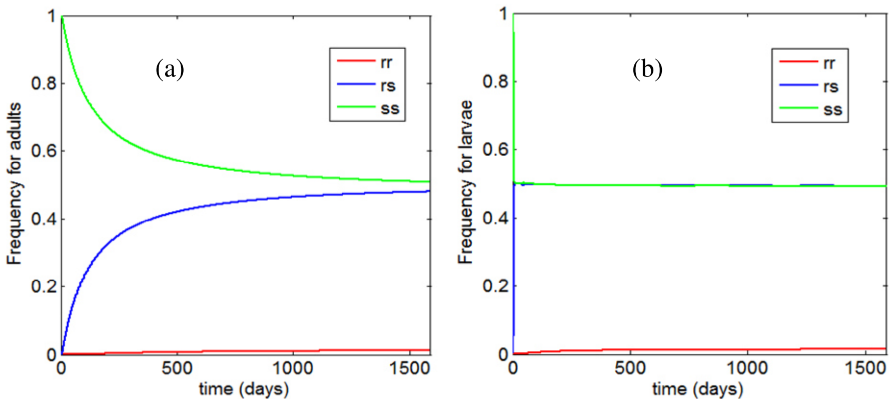

Figure 53: Evolution in 5 years of frequencies of the genotypes in the population with insecticide application (a) for adults and (b) for larvae

Resistance in *Helicoverpa armigera* has been reported by many authors (Wightman et al. 1995). Nimbalkar et al. (2009) estimated the extent of resistance in *Helicoverpa armigera* to commonly used insecticides in main cotton belt of Maharashtra in India and obtained monthly resistance ratios for a period of three months. The resistance ratios obtained with Chlorpyriphos insecticides for example were 3.6 for the first month, 4.1 for the second month and 8.2 for the third month, showing a possible monthly insecticide resistance development. Rourke (2002) mentioned that pupae that overwinter in the soil have a high risk of carrying insecticide resistance into the next season. For Daly (1993), there is some evidence of reduced fitness of resistance pupae during winter diapauses and most of the decline in the resistance frequencies each spring occurs as a result of immigration of susceptible individuals into insecticides treated populations. Unfortunately we could not find data related to the evolution of insecticide resistance within biotypes for our model simulation.

3.11. Optimization of the insecticide application scheme

Increased concern for the environmental effects of pesticides has led to considerable interest in optimal management strategies for controlling pest populations affecting agricultural production (Wetzstein et al. 1985). In its simplest form, optimization means to find a single (and global) minimal or maximal value of an objective function defined over some search space. This usually goes along with also calculating the point in the said search space where the optimal value belongs to (Richter and Yang 2013). Developments of the application of optimal control theory to pests control in agriculture were undertaken by many authors (Shoemaker 1973b, c, Rafikov and Balthazar 2005, Liang and Tang 2010), but usually these studies describe crop damage as a linear function of the pests remaining after applying the control or initiate pesticides application when the pest density reaches the economic threshold. Based on economic methodology, Christiaans et al. (2007) investigated the optimal pesticides application scheme in agriculture but did not take into account any indirect effect of pesticide.

We propose an innovative optimal pest control in agriculture that integrates four main components (crop dynamics, pest dynamics with insecticides resistance, insecticide application scheme) and keeps its complexity under dynamic conditions.

3.11.1. Statement of the Optimal Control Problem

Let us consider the dynamic system formed of equations 4, 6, 12, 21, 22, 55 and 56 described before, with the omission of the dispersal term.

$$\frac{dL}{dt} = f_s r_{\max} L - \mu L \tag{4}$$

$$\frac{dS}{dt} = r_s L\left(1 - \frac{S}{K_s}\right) \tag{6}$$

$$\frac{dB}{dt} = f_b r_b L\left(1 - \frac{B}{K_b}\right) - \frac{\beta BH}{B + K_B} \tag{12}$$

$$\frac{dP}{dt} = \sum_{i=1}^{n} D_s(t) - (k_1 + k_2)P \tag{21}$$

$$\frac{dP_e}{dt} = k_2 P \tag{22}$$

$$\frac{\partial H_i}{\partial t} = r_{H_i}\left(\vec{H}, \vec{A}\right)\left(1 - \frac{H_i}{K_{ap}}\right) - \left(\mu_{H_i} + \gamma_{H_i}\right)H_i - \mu_{p_i} R_i(P) H_i \qquad i = rr, rs, ss \tag{55}$$

Where $R_i(P) = 1 - e^{-\left(\frac{P}{t_{hr_i}}\right)^{\eta_i}}$

$$\frac{\partial A_i}{\partial t} = r\gamma_{H_i} H_i - \mu_{A_i} A_i \qquad i = rr, rs, ss \tag{56}$$

The optimal control problem is to find the optimal quantity of an insecticide to be applied and the optimal time at which the insecticide has to be applied such that the following performance criteria are satisfied.

3.11.2. Performance criteria

For a quantitative evaluation of the system, the following objectives can set up performance criteria for optimization.

- Improvement of yield:
  - Pest control.
- Minimization of the risk for environmental pollution (e.g. water resources):
  - Improvement of insecticides application scheme.

These criteria are governed by the gain function to be maximized:

$$G(u) = C_B B\left(t_f\right) - C_p \sum_{i=1}^{n} D_i - C_l n - C_e P_e\left(t_f\right) \tag{57}$$

subject to the dynamic system considered.

With $u = \{(t_1, D_1), (t_2, D_2), \quad \cdots, \quad (t_n, D_n)\}$. D_i is the dose applied at time t_i, $i = \{1, 2, \cdots, n\}$

Values for the weights C_B, C_p and C_l respectively the price of a kg of cotton, the cost of a dose of insecticides and the cost of an application can easily be derived from the market. The environmental cost C_e characterizes *external costs* (environmental pollution). The magnitude of externalities caused by pesticide use is difficult to estimate but one can assume possible costs to decontaminate groundwater or surface water contaminated with a dose of pesticide. For Shoemaker (1973b), how much pollution will be tolerated in view of rising food costs is a political, not a mathematical, decision.

In Burkina Faso, the costs are as follow:
Price of cotton C_B=245F CFA/kg i.e. 0.37 Euro/kg (UNPCB 2014)
Impact of polluted water is estimated to be 876 331 USD/year i.e. 679200.3416 Euro/year (Lankouande and Maradan 2013). Instate an arbitrary fixed value of C_e=0.1 Euro/dose will be used in our simulation, to represent the possible costs to decontaminate groundwater or surface water contaminated with a dose of pesticide.
Cost of a dose of insecticide C_p=4865F CFA/ha i.e. 7.42 Euro/ha (Biotech Echo 2007)
Cost of an applicator C_{l1}=236 F CFA/ha i.e. 0.36 Euro/ha (Biotech Echo 2007)
Cost of equipment depreciation C_{l2}=375F CFA/ha i.e. 0.57 Euro/ha (Biotech Echo 2007)
Cost of an application C_l=C_{l1}+C_{l2}=0.93 Euro/ha

We will attempt two approaches in solving this control problem: adaptive control and optimal control.

3.11.3. Adaptive control

Adaptive control is applied here for the dynamic system with the time discrete pest population dynamics. In order to uphold the pest population density under a given threshold (threshold 2) which may be the economic threshold, another threshold (threshold 1) above the economic threshold is considered. Two factors and a reference dose are also considered: a factor that will augment the reference dose if the pest population reaches threshold 1 and a factor that will conserve or diminish the reference dose if the pest population density reaches threshold 2 at each control time. Figure 54 illustrates the idea.

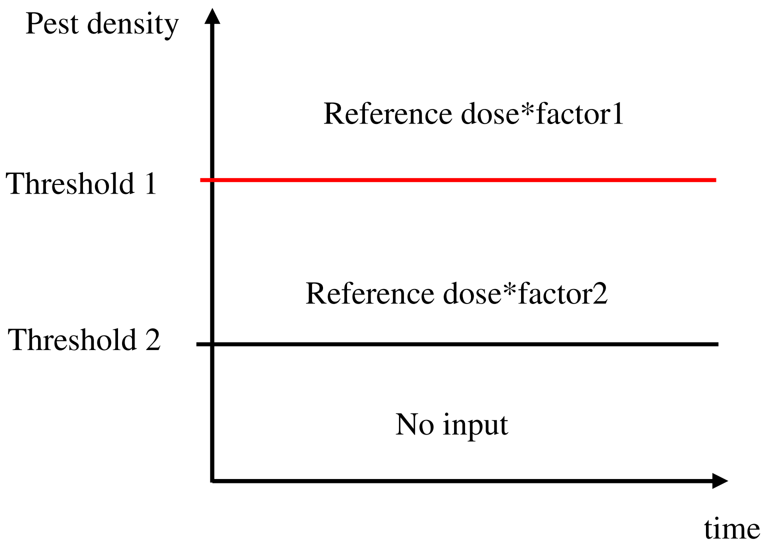

Figure 54: Illustration of the idea in adaptive control

For simulation, we considered threshold 2=5000 larvae/ha, the economic threshold for *H.A*. on a cotton farm (Nibouche 2002, Feng et al. 2010) and threshold 1=10000 larvae/ha, factor1=1.5, factor2=0.1 and pest density is check every 10 days. The reference dose (AS0) is given in table 10. 10 different reference doses are considered.

Table 10: Application schemes obtained applying adaptive control

time	AS1	AS2	AS3	AS4	AS5	AS6	AS7	AS8	AS9	AS10
30	0.05	0.02	0.07	0.09	0.5	0.7	0.9	5	9	10
40	0.075	0.03	0.105	0.135	0.75	1.05	1.35	7.5	-	-
50	0.075	0.03	0.105	0.135	0.75	1.05	1.35	7.5	13.5	15
60	0.075	0.03	0.105	0.135	0.75	1.05	1.35	0.5	13.5	15
70	0.075	0.03	0.105	0.135	0.75	1.05	1.35	0.5	-	-
80	0.075	0.03	0.105	0.135	0.75	1.05	1.35	-	-	-
90	0.075	0.03	0.105	0.135	0.75	1.05	1.35	-	-	-
100	0.075	0.03	0.105	0.135	-	-	-	-	-	-
110	0.075	0.03	0.105	0.135	-	-	-	-	-	-
120	0.075	0.03	0.105	0.135	-	-	-	-	-	-
130	-	0.03	-	-	-	-	-	-	-	-
AS0	0.05	0.02	0.07	0.09	0.5	0.7	0.9	5	9	10
Td	0.725	0.32	1.015	1.305	5	7	9	21	36	40
Gain	1158.93	336.7	1473.5	1673.7	2216.6	2216.2	2208.6	2122.5	2013.8	1984.5

Td is the total dose and AS0 is the reference dose

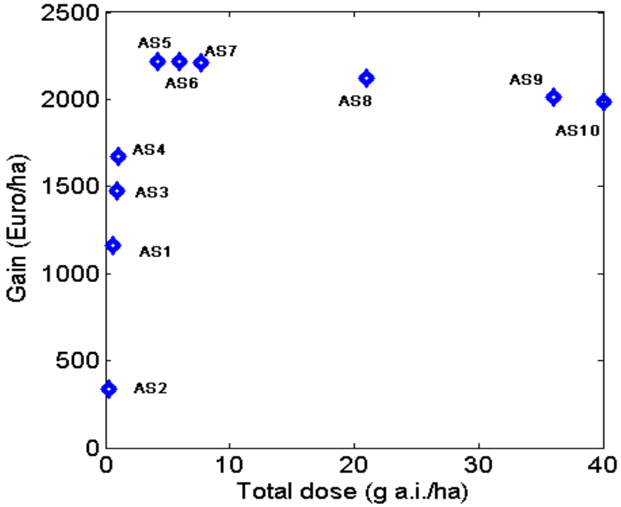

Figure 55: Gain maximization; application of adaptive control

For 10 different input reference doses, there are 10 different optimal results (figure 55 and table 10), and the application scheme that would be considered for pest management is AS5 that produced the maximum gain. The implementation of this control to search for the optimal application scheme necessitates many extra parameters to be optimized, such as: threshold1, threshold2, factor1, factor2 and reference dose. Inserting all theses parameters into our optimization procedure will cost a lot in computation time. Another approach is to use a Matlab optimization solver with fewer constraints.

3.11.4. Optimal control

The Matlab solver *fmincon* is invoked to solve the control problem subject to the dynamic system with the time continuous pest population dynamics (paragraph 3.11.1). The algorithm is the sequential quadratic programming algorithm (SQP). Sequential quadratic programming methods have proved highly effective for solving constrained optimization problems with smooth nonlinear functions in the objective and constraints (Gill et al. 2005).

The lower boundary condition for time is specified by giving the time at which we want to start the outbreak of the pest, here assumed to be at day 30 after planting. The upper boundary for time is specified by giving the time at which the crop is matured and pest attack is no more possible, here assumed to be day 120 after crop planting and the planning horizon is one growing season assumed to be 130 days.

The lower boundary condition for dose is specified by giving the minimal amount of active ingredient that can enter the system in one application, here assumed to be 0 g a.i./ha. The upper boundary condition is specified by giving the maximal amount of active ingredient that is allowable to enter the system in one application, here assumed to be 100 g a.i./ha.

In the solving procedure a number of applications is imposed, in which the solver will search the optimal time and the optimal dose of insecticide to be applied. The application scheme (AS) will be related to the imposed number of applications as for example AS1 implies that one application was imposed; AS2 two applications were imposed and so on until AS10.

3.11.4.1. Optimization without consideration of resistant pest development

Simulations started with 100 susceptible adults and 500 susceptible larvae and outbreaks on day 30 after crop planting. We assumed $\mu_{p_{ss}} = 850/day$ and $thr_{ss} = 0.316$. Results are recorded in the collection of tables 11 and on figure 56.

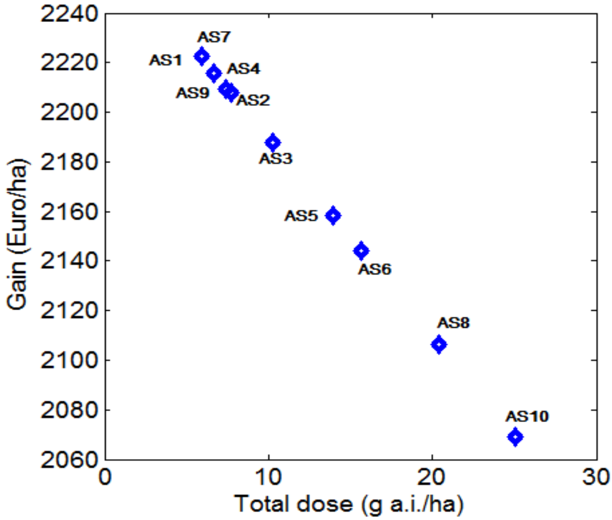

Figure 56: Gain maximization with no resistant pest

Table 11: Collection of optimal application schemes with no resistance development

AS1	time	35	Total dose	Gain
	Dose	6	6	2222.4

AS2	time	35	40	Total dose	Gain
	Dose	4	4	8	2208

AS3	time	31	40	45	Total dose	Gain
	Dose	3.4	3.4	3.4	10.2	2187.8

AS4	time	34	38	47	51	Total dose	Gain
	Dose	2e-8	0.0	6.7	0.0	6.7	2215.8

AS5	time	31	40	45	50	55	Total d.	Gain
	Dose	2.8	2.8	2.8	2.8	2.8	14	2158

AS6	time	35	40	45	50	55	60	Total d.	Gain
	Dose	2.5	2.5	2.8	2.8	2.5	2.5	15.6	2144.3

AS7	time	30.0001	30.04	30.12	30.33	35.4	44.5	66	T. d.	Gain
	Dose	4e-6	0.0	0.0	6	0.0	0.0	0.0	6	2222.5

AS8	time	35	40	45	50	55	60	65	70	T. d.	Gain
	Dose	2.5	2.5	2.5	2.6	2.5	2.5	2.5	2.5	20.1	2106.4

AS9	time	31	32	43	48	50	52	65	63	74	T.d.	Gain
	Dose	0.0	0.0	3e-6	7	0.39	0.0	00	00	00	7.3	2069.1

AS10	time	35	40	45	50	55	60	65	70	75	80	T. d.	Gain
	Dose	2.5	2.5	2.5	2.5	2.52	2.52	2.5	2.5	2.5	2.5	25.04	2069

Results are obtained with decimal numbers but integers are recorded for the time step is considered to be days. The time step of AS7 is recorded with the decimal part because of the closeness of the numbers. Due to the fact that the number of application is imposed, the solver will honor this condition and in this way values may be very close to each other for time step or be very small for dose. The output 0.0 is due to the number of decimal digits that is fixed for the output of our computer program. This number is fixed to 15 digits and it happened that during the optimization procedure, a dose be less than a factor of 10^{-15}. But in practice, AS7 cannot be considered to initiate a crop treatment. The optimal application scheme in this simulation appears to be AS1 with one insecticide application at day 35 and a dose of 6g a.i./ha. The resulting gain is 2222.4Euro/ha.

The applications schemes AS1 to AS10 suggest that early insecticide applications are advisable, since the pest outbreaks at day 30 after crop planting and the optimal application scheme starts at day 35 for AS1, AS2, AS6, AS8, AS10, at day 34 for AS4, at day 31 for AS3, AS5, AS9 and at day 30 for AS7. The effectiveness of early applications was also recognized by several authors such as Regev et al. (1976) and Chatar et al. (2010). Therefore, it may not be necessary to wait for the pest density to reach the economic threshold to initiate crop treatments as it is the case in Huet and Regev (1974), Lima et al. (2009), Feng et al. (2010). Moreover, with the association of an efficient active ingredient and a better positioning of crop treatments, it is possible to reduce the quantity of insecticide sprays (and of course not only the cost of production, but also the unintended effects of these pesticides in the environment) without endangering the production (Vaissayre et al. 2006).

The optimal solution is obtained by making an initial guess of the solution; the maximal gain obtained is local. A global maximum can be reach by applying a random generator to the initial guess solution and perform many simulations. The global maximum would be the most appearing. Other way is to invoke a Matlab *MultiStart* object. This object contains properties (options) that affect how the run method repeatedly runs a local solver, or generates a *GlobalOptimSolution* object (Matlab documentation 2014).

3.11.4.2. Optimization with resistant pest development

Simulations started with $H_{0_{ss}} = 500/ha$ $A_{0_{ss}} = 100/ha$, $H_{0_{rr}} = H_{0_{rs}} = A_{0_{rr}} = A_{0_{rs}} = 10/ha$ $\mu_{p_{rr}} = 0/day$ $\mu_{p_{rs}} = 300/day$, $\mu_{p_{ss}} = 850/day$, $thr_{ss} = 0.316$ and $thr_{ss} = 0.632$. Pest outbreaks at day 30 after crop planting. Results of different application schemes are recorded in the figure 57.

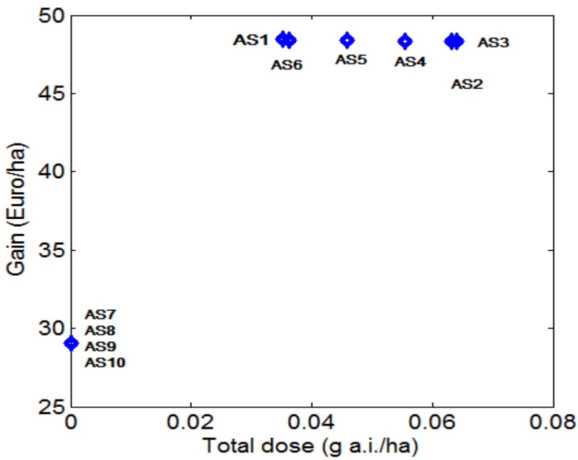

Figure 57: Gain maximization with resistant pest dynamics

The optimal application scheme in figure 57 appears to be AS1, with a dose of 0.034g a.i./ha at day 40 after crop planting, and the resulting gain is 48.4 Euro/ha. The gain has considerably decreased and what is remarkable is that the model did not try to increase the insecticide dose. Increasing crop treatments when the efficiency of an insecticide is reduced is a regrettable common farming practice, susceptible of environmental pollution. Denholm et al. (1998) point out that for many key agricultural pests, successful management of insecticide resistance depends not only on modifying the way that insecticides are deployed, but also on reducing the total number of treatments applied.

3.12. Sensitivity analysis

The goal of sensitivity analysis is to answer the question: how important are the individual elements of the input with respect to the uncertainty in the output? (Helton et al. 2006). Precisely in crop modeling, the aim of sensitivity analysis is to determine how sensitive the output of a crop model is, with respect to the elements of the model which are subject to uncertainty or variability (Monod et al. 2006). We will apply sensitivity analysis to rank parameters of the dynamic system applied in paragraph 3.11.4.1 to indicate how important are these parameters to the maximal gain. Therefore which factors have a very important influence on the controlled solution and thus which factors should be measured (determined) very precisely.

The maximal gain obtained in paragraph 3.11.4.1 is considered to be the reference gain, that is Gain1=2222.4Euro/ha. Gain2 is the maximal gain obtained by increasing each parameter value to 50%. The difference Gain2-Gain1 in absolute value indicates the extent of change in the maximal gain subject to the change of a parameter value. Results are recorded in table 12 and in the Appendix 1.

Table 12: Gain sensitivity to parameters

Parameter	Definition	Gain2	Absolute value Gain2-Gain1
r_{imax}	Maximal oviposition rate in a biotype	51.064	2171.336
P_c	Price of cotton	3381.974	1159.574
K_b	Field carrying capacity for boll	3232.871	1010.471
t_s	Switching time	1796.284	426.116
μ_p	Mortality rate due to insecticide	2265.020	42.620
r_{max}	Maximal growth rate for leaves	2190.553	31.847
φ	Form parameter of dose response function	2248.109	25.709
C_e	Environmental cost	2247.654	25.254
C_l	Cost of insecticide application	2247.644	25.244
thr	Threshold of effective dose (scale parameter)	2200.118	22.282
r_b	Growth rate for boll	2242.871	20.471
a	Empirical parameter	2242.572	20.172
C_p	Cost of a dose of pesticide	2238.838	16.438
μ	Attrition rate of leaves	2217.214	5.186
K_B	Half saturation constant for boll	2223.14	0.74
r	Proportion of females	2222.916	0.516
V_{max}	Maximal consumption rate	2222.625	0.225
r_s	Growth rate for stem	2222.572	0.172
α_B	Coefficient for the capacity	2222.259	0.141
γ_H	Emergence rate	2222.423	0.023
Ks	Field carrying capacity for stem	2222.378	0.022

The model outputs are obtained with respect to changes in parameter values. The results show that the population parameter, the maximal oviposition rate (r_{imax}) has a substantial impact on the gain. It is important to mention that the initial conditions are crucial in accurate decision making.

4. Conclusion and further extensions

A life cycle model for crop dynamics in interaction with pest population dynamics and pesticides action is developed. The model includes spatial dispersal of pest and resistant gene flow. The models are form of Ordinary Differential Equations (ODEs) for crop dynamics and partial differential equations (PDEs) for pest dynamics and for pesticides transport in the soil.

An attempt to develop a hybrid model was initiated, comprising a time discrete model for pest population dynamics coupled to a time continuous model for crop dynamics and pesticides action. The model behaved meaningful regarding the impact of pest on crop dynamics and pesticides action. It would be interesting to further develop this hybrid model by making pest dynamics crop dependent and by including resistant gene flow and spatial dispersal.

Optimization of pesticides application scheme under deterministic conditions has been achieved, with example of application to cotton crop and to the pest *Helicoverpa armigera*. More testing and applications to different cotton regions is needed to build confidence in the use of this DSS. Such confidence may then lead to extension of this methodology to other crops and pests. Certainly, this will require collaboration of several research and extension groups.

It is difficult, or even impossible to control target pests applying pesticides without also disrupting beneficial populations. One can then think of integrating multiple species such as insect prey-predator relationships, as mentioned by Feder and Regev (1975). There is also a need to identify when to change pest management strategy regarding resistance development and consider alternative pest control techniques, such as parasites and predators. Some difficulty may be to identify whether the initial population is resistant or not and the proportion of each biotype.

Much work remains with regards to validation and revision of the model described here, but in its current form it stands as an important starting point for improving economically and ecologically viable the use of chemicals in agriculture.

Since the number of possible control strategies increases exponentially with increases in the number of control techniques used, planning an integrated pest management program is much more complicated and difficult than planning a program that utilizes only one control technique. Mathematical optimization models can reduce this difficulty by giving some insight as to what combinations might be best and should be, therefore, experimentally tested (Shoemaker 1973a).

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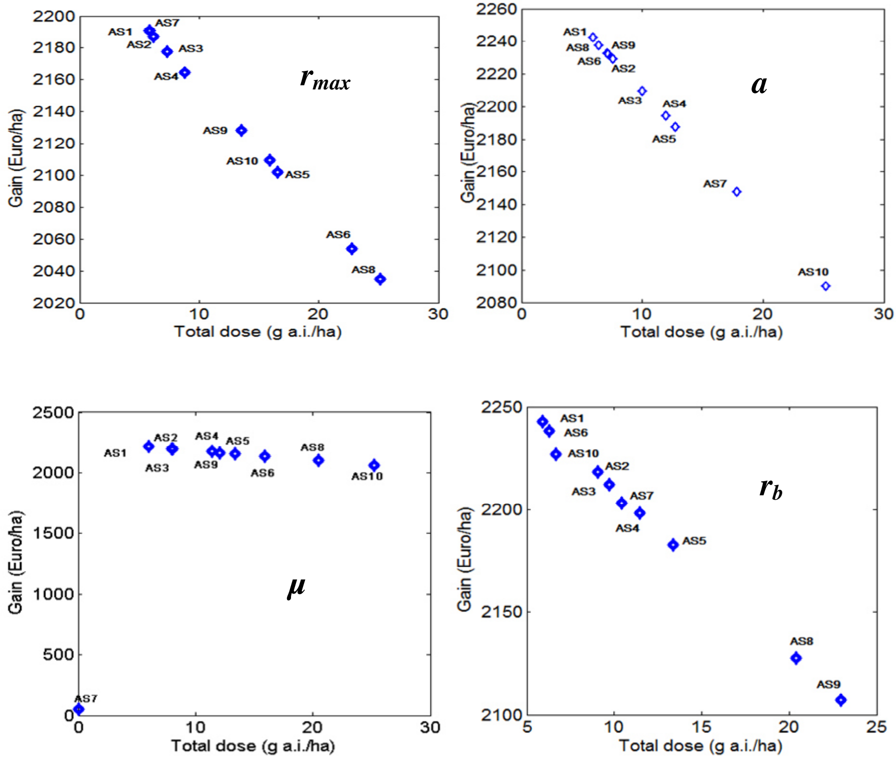
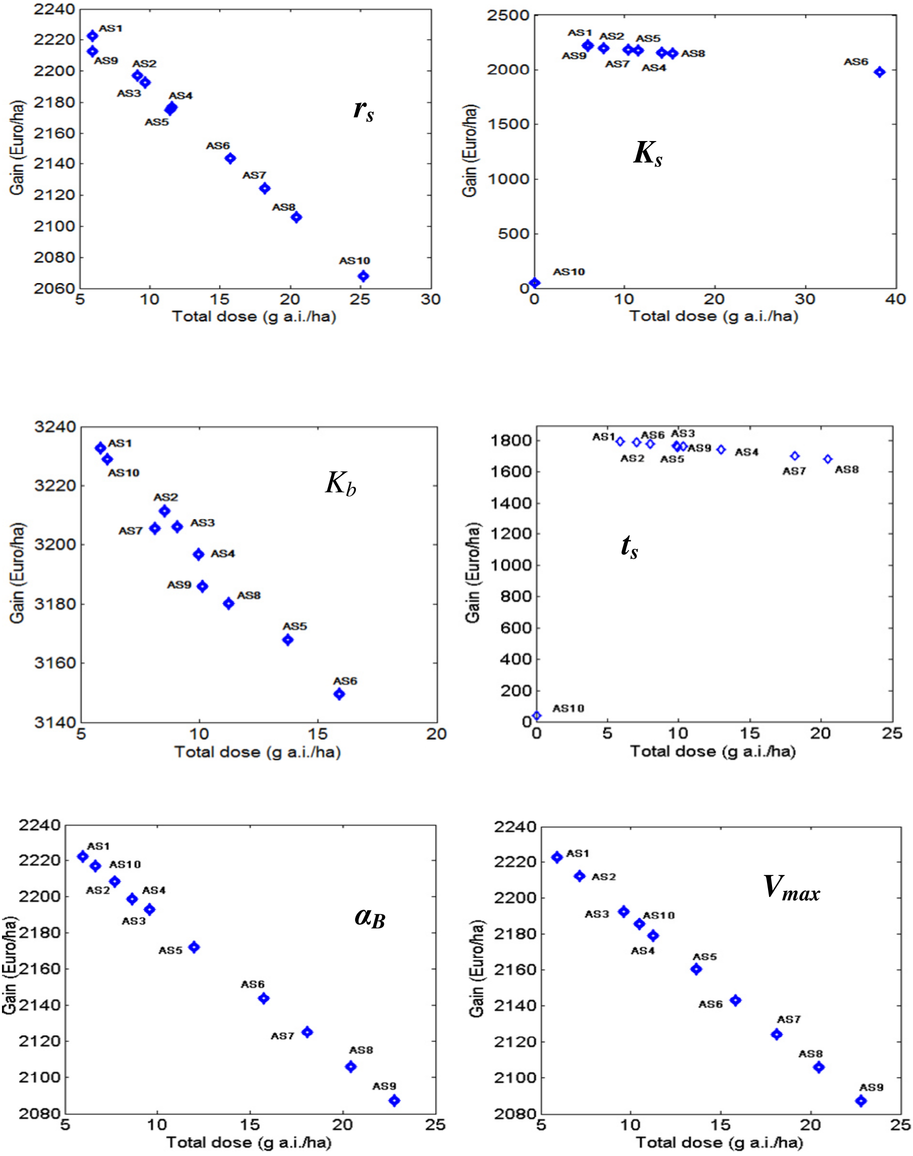
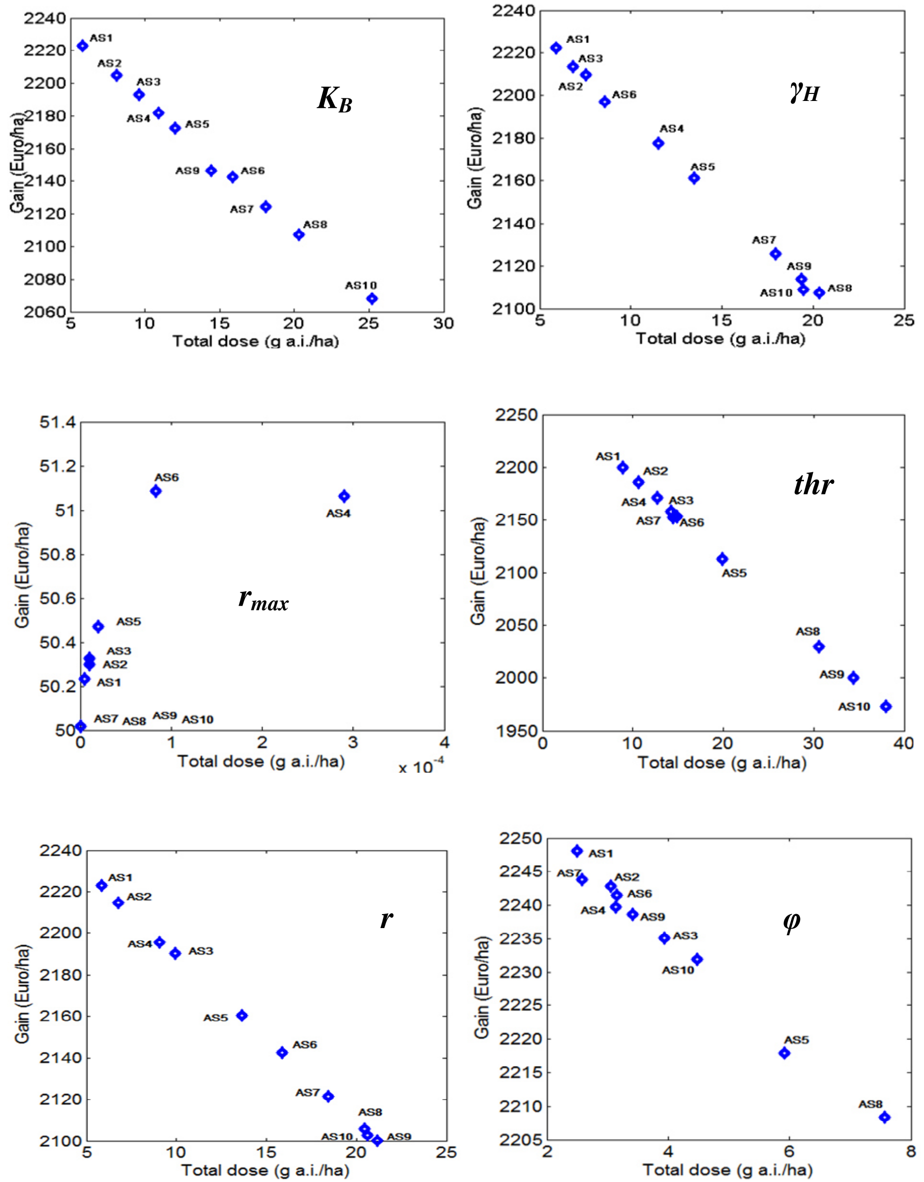
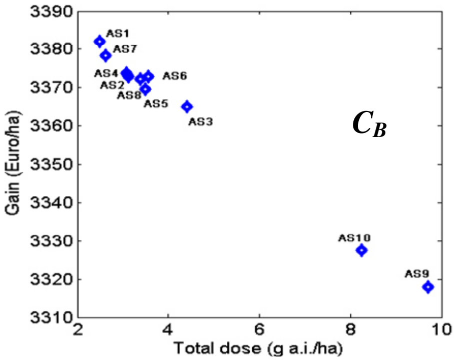
6. Appendix 1: sensitivity analysis; figures for gain maximization

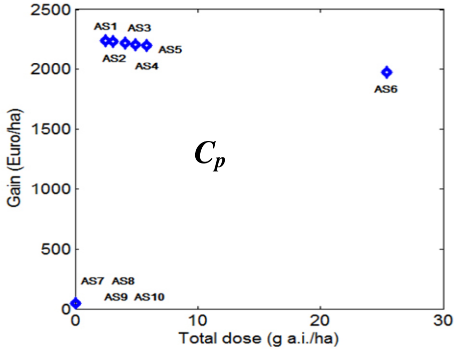



Gain (Euro/ha)
Total dose (g a.i./ha)
r_s
K_s
K_b
t_s
α_B
V_{max}
AS1
AS2
AS3
AS4
AS5
AS6
AS7
AS8
AS9
AS10

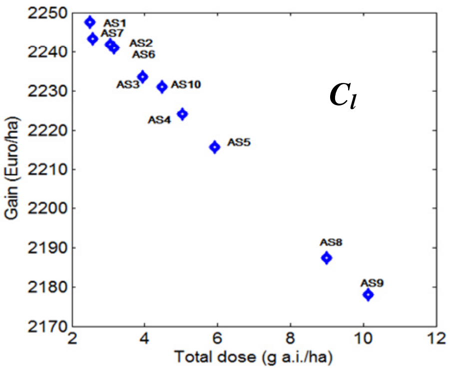

K_B
γ_H
r_{max}
thr
r
φ
Gain (Euro/ha)
Total dose (g a.i./ha)
x 10^-4
AS1
AS2
AS3
AS4
AS5
AS6
AS7
AS8
AS9
AS10



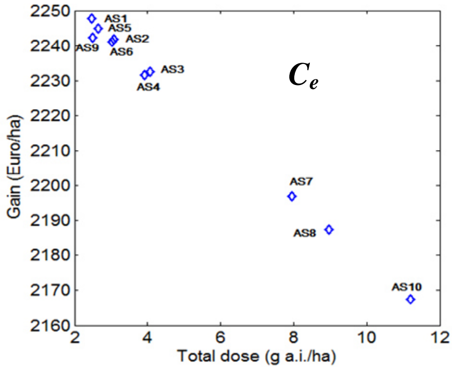
C_B
Gain (Euro/ha)
Total dose (g a.i./ha)
3390
3380
3370
3360
3350
3340
3330
3320
3310
2
4
6
8
10
AS1
AS7
AS4
AS2
AS8
AS5
AS6
AS3
AS10
AS9



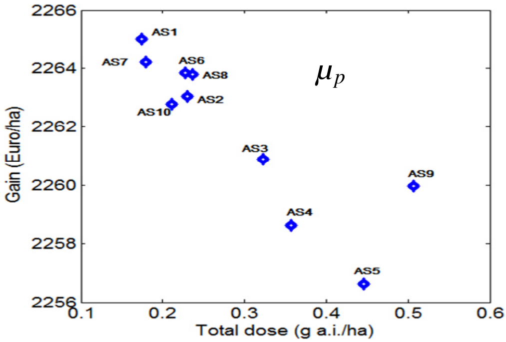
C_p
Gain (Euro/ha)
Total dose (g a.i./ha)
2500
2000
1500
1000
500
0
0
10
20
30
AS1
AS3
AS5
AS2
AS4
AS6
AS7
AS8
AS9
AS10



C_l
Gain (Euro/ha)
Total dose (g a.i./ha)
2250
2240
2230
2220
2210
2200
2190
2180
2170
2
4
6
8
10
12
AS1
AS7
AS2
AS6
AS3
AS10
AS4
AS5
AS8
AS9



C_e
Gain (Euro/ha)
Total dose (g a.i./ha)
2250
2240
2230
2220
2210
2200
2190
2180
2170
2160
2
4
6
8
10
12
AS1
AS5
AS9
AS2
AS6
AS3
AS4
AS7
AS8
AS10



μ_p
Gain (Euro/ha)
Total dose (g a.i./ha)
2266
2264
2262
2260
2258
2256
0.1
0.2
0.3
0.4
0.5
0.6
AS1
AS7
AS6
AS8
AS2
AS10
AS3
AS9
AS4
AS5

7. Appendix 2: Numerical realizations

7.1. Resolution of the system of Ordinary differential equations (ODEs)

The system of ODEs was solved invoking the Matlab numerical ODE solver ode45. ode45 is recommended to be tried first when solving differential equations in Matlab. This routine uses a variable step 4^{th} and 5^{th} order Runge-Kutta Method to solve differential equations numerically.

First, a function containing the equations (derivatives) is created, then the function is called in the main program as a function handle in the following syntax.

options=odeset('RelTol', 1.e^{-6})

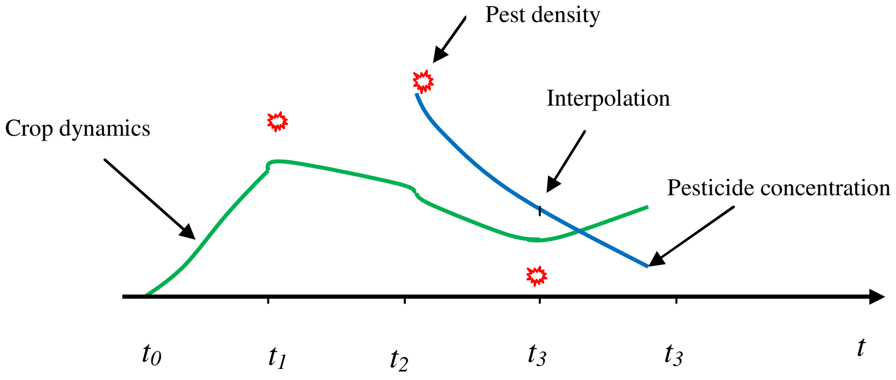
[t, y]=ode45(@function, Tspan, y_0, options)

Where :
t is the independent variable (time)
y is the solution array of the ODE (the value of the state at every time)
ode45 is the Matlab solver (there are many other solvers that could be used)
function is the handle for function containing the derivatives
Tspan is a vector specifying the interval of integration
y_0 is a vector of initial conditions

options is structure of optimal parameters that change the default integration properties

7.2. Coupled time discrete and time continuous model computed as a sequence of initial values problem

The hybrid model is solved as a sequence of initial values problem. The time discrete pest population dynamics is computed at regular time steps (days) but the computation time step of crop dynamics may not be regular. The time continuous model is an ODE solved via the Matlab solver ode45. The initial values at time t_0 of both crop and pest densities are given as input variables, and Tspan is the interval [t_0, t_1]. The program will then solve the problem in Tspan, and the next initial values will be the crop and pest densities at time t_1 and the resolution will start again with these new initial values in a new Tspan=[t_1, t_2] and so on until the end of the simulation period. The pesticide is applied by interpolating to find the value of the underlying function (function for pesticide application described in paragraph 3.5) at each time step. The process is illustrated in the figure below.



Matlab code of the hybrid model

For our convenience, the code is written as a function with subfunctions.

```
function [tt,yp]=calenD
global k s rmax a ro mu alfa rb Ks Kb ts Vmax KB AS

gam=0.32;
Dt50=1;
schwelle=40.73;
k=log(2)/Dt50;
s=1;
tmin=0;
tmax=130;

%insecticide application scheme
AS=[45 59 73 87 101 115;60 60 60 60 60 60];

y0=0;
tspan=[tmin; tmax];
    options=odeset('OutputFcn','');
    [tt,yp] = ode45(@(tt,yp)fAp(tt,yp),tspan,y0,options);

    %insecticide application function
      function app=fAp(tt,yp)
          v=0;
          n=length(AS);

          for i=1:n
              v=v+1/sqrt(2*pi)/s*AS(2,i)*exp(-(tt-
AS(1,i))^2/2/s^2);
          end
          app=v-k*yp;
      end

  %crop dynamics function
    function cottonn3=fcottonn3(t,y,rav)
```

```
      fs=(1+a)*exp(-ro*(t-tmin))/(1+a*exp(-ro*(t-tmin)));
      fb=1-exp(-((t-tmin)/ts)^4);

      cottonn3=[fs*rmax*y(1)-mu*y(1);alfa*y(1)*(1-
y(2)/Ks);...
          fb*rb*y(1)*(1-y(3)/Kb)-
Vmax*rav*y(3)/(y(3)+KB)*(y(3)>0)];
    end

%plot insecticide application
 plot(tt,yp)
 xlabel('time (days)')
 ylabel('concentration (kg a.i/ha)')

% time discrete pest population dynamics (the extended
Leslie model)
nclegg=2;
ncllarvae=14;
nclpupae=9;
ncladult=14;
stages=8; %number of life stages

ac=[2; 2; 2; 2; 3; 5; 9; 14]; %number of ageclasses per
stage
dim=sum(ac); %dimension of the matrix
nn=zeros(stages+1,1); %cumulative sum
for i6=1:stages
    nn(i6+1)=nn(i6)+ac(i6);
end

%survival probabilities
surv=[0.5655;0.7011;0.9016;0.9636;0.9811;0.9615;0.8958;1]
;%Miron

%transition probabilities
U=[0.5655;0.7011;0.9016;0.9636;0.9811;0.9615;0.8958];

%fertility
```

```
fert=[26; 26; 26; 26; 26; 26; 26; 26; 26; 26; 26; 26; 26;
26];

%Matrix initialisation
M=zeros(dim,dim);

%M1 matrices
for s1=1:stages
    for i5=nn(s1)+2:nn(s1+1)
        M(i5,i5-1)=surv(s1);
        M(nn(s1+1),nn(s1+1))=0*surv(s1);
    end
end

%M2 matrices for adults
ii=1;
for i4=nn(stages)+1:nn(stages+1)
    M(1,i4)=fert(ii);
    ii=ii+1;
end

%M2 matrices for the other stages
for s1=1:stages-1
    M(nn(s1+1)+1,nn(s1+1))=U(s1);
end

X0=zeros(dim,1);
for ij=1:10 %nn(3)
    X0(nclegg+ncllarvae-ii,1)=100;
end

rmax=0.428;
ro=rmax;
a=188;
mu=0.000881;
alfa=0.051;
rb=1.06;
Ks=3660;
Kb=6190;
ts=92.2;
```

```
Vmax=.9919*2;
KB=2516*15;

leaves=zeros(tmax,1);
stem=zeros(tmax,1);
boll=zeros(tmax,1);
time=zeros(1,tmax);
tp=30; %date of pests outbreaks (days after planting)
tmin=0;
B0=[5; 0; 0]; % inintial value for crop dynamics before
pests outbreaks
Tspan=[tmin,tp];
options=odeset('OutputFcn','');
[t,y]=ode45(@(t,y)fcottonn3(t,y,0),Tspan,B0,options);
for ik=1:tp
    leaves(ik)=interp1(t,y(:,1),ik);
    stem(ik)=interp1(t,y(:,2),ik);
    boll(ik)=interp1(t,y(:,3),ik);
    time(ik)=ik;
end
nmax=length(t);
B0=[y(nmax,1);y(nmax,2);y(nmax,3)];% initial value for
crop dynamics after pests outbreaks

eggs=zeros(1,tmax);
larvae=zeros(1,tmax);
pupae=zeros(1,tmax);
adults=zeros(1,tmax);
pop=zeros(1,tmax);

for tr=tp:tmax % pest counter

    yegg=0;
    ylarvae=0;
    ypupae=0;
    yadult=0;
    ypop=0;

    C=interp1(tt,yp,tr); %insecticide application
```

```
 for s1=2:6 %6 instar larvae
     for i2=nn(s1):nn(s1+1)-1
         M(i2+1,i2)=exp(-(C/schwelle)^gam)*M(i2+1,i2);
     end
 end

Xn=M*X0;
X0=Xn;

for j=1:nclegg
    yegg=yegg+X0(j);
end
for j=1:ncllarvae
    ylarvae=ylarvae+X0(nclegg+j);
end
for j=1:nclpupae
    ypupae=ypupae+X0(nclegg+ncllarvae+j);
end
for j=1:ncladult
    yadult=yadult+X0(nclegg+ncllarvae+nclpupae+j);
end
for j=1:dim
    ypop=ypop+X0(j);
end

    eggs(tr)=yegg;
    larvae(tr)=ylarvae;
    pupae(tr)=ypupae;
    adults(tr)=yadult;
    pop(tr)=ypop;
    time(tr)=tr;

    rav=larvae(tr);

  Tspan=[tr-1,tr];
  options=odeset('OutputFcn','');
  [t,y]=ode45(@(t,y)fcottonn3(t,y,rav),Tspan,B0,options);
  nmax=length(t);
  B0=[y(nmax,1);y(nmax,2);y(nmax,3)]; % initial value for
the next computation
```

```
  leaves(tr)=y(nmax,1);
  stem(tr)=y(nmax,2);
  boll(tr)=y(nmax,3);

end

figure
plot(time,boll)
xlabel('time (days)')
ylabel('boll density (kg/ha)')

figure
plot(time,larvae,'r+')
xlabel('time (days)')
ylabel('number of larvae/ha')
hold on

figure
plot(time,eggs,'b.')
xlabel('time (days)')
ylabel('number of larvae individuals/ha')
hold on

plot(time,pupae,'m*')
xlabel('time (days)')
ylabel('number of larvae individuals/ha')
hold on

plot(time,adults,'kp')
xlabel('time (days)')
hold on
ylabel('number of individuals/ha')
legend('Eggs','Larvae','Pupae','Adults',4)
end
```

7.3. Optimization

The explanation of the procedure is given in paragraph 3.11.4. The code is as follow:

```
%Create a .m file for the main program
global n t0
Dtotal=zeros(1,2);
Eval=zeros(1,2);
Nap=5; %choose the number of crop treatments
for n=1:Nap
    total=0;
t0=30; % date of pests outbreaks
    lb = zeros(1,2*n);  % Set lower bounds
    ub=zeros(1,2*n); % Set upper bounds
    for ii=1:n
        lb(1,2*ii-1)=t0; % lower bounds for time
        lb(1,2*ii)=0; % lower bounds for insecticide dose
        ub(1,2*ii-1)=130; % upper bounds for time
        ub(1,2*ii)=100; % upper bounds for insecticide
dose
    end
%Make a starting guess at the solution
    x0 = zeros(1,2*n);
    for j=1:n
       x0(1,2*j-1)=t0+5*j;
       x0(1,2*j)=50;
    end
    options =
optimset('Algorithm','sqp','DerivativeCheck','off','Displ
ay','iter-detailed');
 [x, fval] =
fmincon(@perform,x0,[],[],[],[],lb,ub,[],options)
Gain(1,n)=-fval;
rate(1,n)=n;
for i=1:n
    total=total+x(2*i);
end
Eval(1,1)=total;
Eval(1,2)=fval;
```

```
Dtotal=cat(1,Dtotal,Eval)
End

Figure
%plot total dose vs gain
plot(Dtotal (:,1),-Dtotal(:,2),'+')

%Create a .m file function to evaluate the performance of
the objective function
function G=perform(x)
global n Dtot t0

%set the prices and costs
Pc=0.37;
Cp=7.42;
Cl=0.93;
Ce=.1;

tmin=0;
tmax=130
H0=1000; %initial pest density
y0=[5;0;0;0;0;0]; %Initial value before pests outbreaks
Tspan=[tmin t0];
options=odeset('RelTol',1.e-6);
 [t,y] = ode45(@(t,y)testopt(t,y,x),Tspan,y0,options);
ytime=t;
yleaves=y(:,1);
ystem=y(:,2);
yboll=y(:,3);
ypest=y(:,4);
yconc=y(:,5);
yenv=y(:,6);

m0=length(y);
y0=[y(m0,1);y(m0,2);y(m0,3);H0;y(m0,5);y(m0,6)]; %initial
values when pests outbreaks
tspan=[t0 tmax];
[t,y] = ode45(@(t,y)optfunc(t,y,x),tspan,y0,options);

ytime=cat(1,ytime,t);
```

```
yleaves=cat(1,yleaves,y(:,1));
ystem=cat(1,ystem,y(:,2));
yboll=cat(1,yboll,y(:,3));
ypest=cat(1,ypest,y(:,4));
yconc=cat(1,yconc,y(:,5));
yenv=cat(1,yenv,y(:,6));

m=length(y);

subplot(2,2,1),plot(ytime,yboll)
%hold on
title('boll')

subplot(2,2,3),plot(ytime,ypest)
%hold on
title ('pest pop')

subplot(2,2,2),plot(ytime,yconc)
%hold on
title('pesticide')

subplot(2,2,4),plot(ytime,yenv)
%hold on
title('pestenv')

G=-(Pc*y(m,3)-Cp*Dtot-Cl*n-Ce*y(m,6));

% Create a .m file function containing derivatives
function cottonrav=optfunc(t,y,x)
 global n Dtot

%set parameters values
rmax=0.428;
a=188;
ro=rmax;
mu=0.000881;
rb=1.06;
alfa=0.051;
Ks=3660;
```

```
Kb=6190;
ts=92.2;

Vmax=0.9919*2;
gamma=60;
delta=.29;
KB=2516*25;
mup=.7*10;
s=1;
gam=0.19;
Dt50=20;
Schwelle=31.6;
k2=0.102;

k1=log(2)/Dt50;
tmin=0;

 fs=(1+a)*exp(-ro*(t-tmin))/(1+a*exp(-ro*(t-tmin)));
 fb=1-exp(-((t-tmin)/ts)^4);

v=0;
for i=1:n
    v=v+1/sqrt(2*pi)/s*x(2*i)*exp(-(t-x(2*i-1))^2/2/s^2);
end
Dtot=0;
for i=1:n
    Dtot=Dtot+x(2*i);
end

 cottonrav=[fs*rmax*y(1)-mu*y(1);alfa*y(1)*(1-
y(2)/Ks);...
     fb*rb*y(1)*(1-y(3)/Kb)-Vmax*y(3)*y(4)/(y(3)+KB);...
     gamma*y(3)*y(4)/(y(3)+KB)-delta*y(4)-mup*y(4)*(1-
exp(-(y(5)/Schwelle)^gam)); v-(k1+k2)*y(5);k2*y(5)];
end
```

7.4. Spatial process

The finite elements tool COMSOL multiphysics was used to simulate pest dispersal (paragraph 3.9.2.1) and solute transport (paragraph 3.8.1). COMSOL Multiphysics is an interactive environment for solving systems of partial differential equations (PDE) up to three dimensions. It is especially designed for multiphysics problems, i.e. systems that consist of coupled phenomena described by different models. The numerical methods are finite elements with adapting meshes and error control based on the Petrove-Galerkin approach (COMSOL, 2005). PDEs are either provided by a model library or can be formulated in general form by the user. The system offers a set of solvers including a solver for non-stationary non-linear problems, which are the kind of problems encountered in biological dispersal models. The time dependent solver uses variable-order variable-stepsize backward differentiation formulas (Brown et al. 1994, Brenan et al. 1996)